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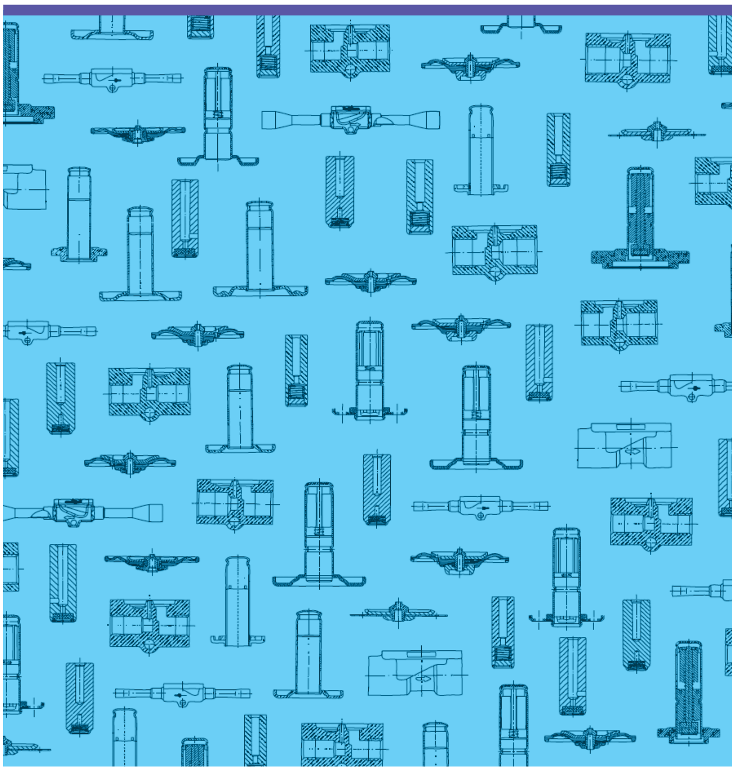

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Morten Kvist
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Product Family Assessment

Ph.D. thesis

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Abstract

This thesis reports the results of a PhD project from the Technical University of Denmark. The research has been carried out in a collaborative project with the Danish company Danfoss Automatic Controls.

In the global market companies are struggling to meet customers' expectation of products that are – at a relatively low price - custom fitted to suit their exact needs and at the same time maintain a profitable business. In the pursuit of growth companies tend to focus on customer demand and market driven product development. While operating in the mass production paradigm and focusing on the cost of the single product this will in time lead to a patchwork of product variants, features, parts, and process technologies – i.e. a product family so complex that it becomes a burden in the companies' daily operation.

As a consequence there has been an increase in the number of companies that are beginning to change their focus from single products to entire product families and try to incorporate the development of product variety into a future product family. The key is to create fit between the product design and production setup.

The challenge of understanding this fit and modelling dispositional relations between the existing product design and the production setup with an eye re-design the products and/or the production setup is the main topic for this research project.

This research contributes with a visual modelling formalism which has its basis in the Product Family Master Plan (PFMP) presented in the work of Ulf Harlou [2006], hence the notion: PFMP^2 – the extended Product Family Master Plan. The model can used to build an overview of dispositional relations between the design of a product family and the production setup. Furthermore, the model links the product design to commercial and quality aspects of the business. Hereby the model supports assessment of the elements in the product family and identification of the good solutions which can be included and the more unfortunate elements that should be avoided in a future product design.

The research builds on engineering design science research literature and on the ideas of lean production, plus experiences from the industrial collaboration. The idea of waste from the lean philosophy is brought into a product variety context, and discussed in relation to product development.

Verification of the model has been carried out in an industrial setting at Danfoss Automatic Controls. Furthermore, the research has been reviewed by a panel of academic researchers and industrial practitioners as well as through discussion in academic communities. The overall response to the tool has been positive and the single case study at Danfoss reports good usefulness and results.

Keywords: Product modelling, production modelling, value stream mapping, product family, product architecture, product platform, product variety, engineering design.

Resume

Denne afhandling beskriver resultaterne af et PhD projekt fra DTU – Danmarks Tekniske Universitet. Projektet er lavet i tæt samarbejde med Danfoss Automatic Controls.

I det globaliserede marked kæmper virksomheder med at imødekomme kundernes forventninger til produkter – til en relativ lav pris – som er mere eller mindre skræddersyet til at passe kundens specifikke behov, og på samme tid opretholde en profitabel forretning. I jagten på vækst er virksomhederne tilbøjelige til at fokusere på kundeefterspørgsel og markedsdrevet produktudvikling, dvs. udvikling af nye produkter og/eller markeder. Fokuserer man samtidig på omkostninger af det enkelte produkt som i masseproduktionstankegangen ender man – uden den nødvendige styring - efter nogen tid op med et kludetæppe af produktvarianter, features, komponenter og fremstillingsprocesser, dvs. en produktfamilie, der er blevet så kompleks at den er blevet en byrde i den daglige arbejdsgang.

Som en konsekvens heraf er flere virksomheder begyndt at tænke mere i produktfamilier i stedet for enkelte produkter. Nøglen til at opnå de ønskede synergieffekter er at tilpasse produkternes design og produktion hinanden.

Udfordringen der er forbundet med at få en forståelse at denne tilpasning, samt modellering af disponeringsrelationer mellem produktdesign og produktionsapparat med henblik på omdesign af produkterne og/eller produktions er hovedemnet for dette PhD projekt.

Resultatet af projektet består bl.a. af et modellieringsværktøj, der har sit udspring i Product Family Master Plan (PFMP), som er beskrevet i Ulf Harlous PhD afhandling. Modellen har derfor fået navnet PFMP2 – the extended Product Family Master Plan. Modellen benyttes til at opbygge et overblik over disponeringsrelationer mellem produkternes design og produktionsapparatet. Ydermere, binder modellen også produkternes design sammen med kommercielle og markedsmæssige aspekter af forretningen. Herved understøtter modellen en vurdering af hvor meget eller lidt elementer i produktprogrammet bidrager til den samlede forretning.

Forskningsarbejdet bygger på engineering design science research og ideer bag Lean production, samt erfaringer gjort i forbindelse med det industrielle samarbejde. Specielt er Lean-begrebet waste bragt ind og diskuteret i kontekst med produktvarians og produktudvikling.

Verifikation af den udviklede model er sket i samarbejde med Danfoss Automatic Controls. Ydermere, er resultaterne revideret gennem et panel af akademiske forskere og udvalgte industrielle interessenter, samt diskussion i diverse akademiske fora. Tilbagemeldingerne er overordnet positive og den ene implementering i Danfoss Automatic Controls viser gode resultater.

Table of contents

Part 7

Part 8

Part 1

Introduction to the research

Part 1 presents an introduction to the research that is reported on in this thesis. Part 1 describes the business challenge of uncontrollable growth of product complexity, as well as the research challenge of modelling product families, which form the background of this research work. Concluding, part 1 presents two research questions that are to be answered in the research work at hand.

1.1. Introduction to the research

The aim of this research is to model product families in terms of the product structure, the value it's offering, and how the value is created in order to get an overview, which can support diagnosis on the product family's performance regarding effective manufacturing of the variety of products in the product family.

The reason for doing this is to support decision-making in industrial companies regarding re-structuring and re-design of the company's product family in order to create a better fit to especially the production setup and the actual demand in market, in order to secure efficient production of the proper product variety.

The case in many market-oriented companies is that they in time become burdened by product complexity due to uncontrollable expansion of the product family and lack of data managing discipline [Meyer & Lehnerd, 1997], [Hvam et al., 2007], [Ericsson & Erixon, 1999], [Anderson & Pine,1998]. The thesis behind the research is that that structuring the product data in a visual model can support these companies in making better and well-founded decisions about the product family in order to create a better fit to the company's market strategy and production setup in particular, and furthermore, bring the level of product complexity down to a minimum.

Most of the sparse academic research concerned with assessment of product families has its focus around economic models and key figures based on engineering costs, development time, manufacturing costs, marketing costs, sales data, and margins [Meyer and Lehnerd, 1997], indicating if the product family is profitable or not. The problem is that it does not give a proper diagnosis or indication of where it is possible to improve the products to get higher performance.

The Product Family Master Plan (PFMP) tool [Harlou, 2006] on the other hand, focus on the structure of the products and how well it fit the market demand and production setup. This research will take its starting point in the PFMP tool and aim to further develop this tool on the basis of industrial case studies, where the PFMP tool is used for analysing and diagnosing a product family.

1.2. The business challenge: "Uncontrollable growth of product complexity"

In a global business world manufacturing companies face ever growing opportunities and threats. While having the opportunity to satisfy increasingly diverse customer needs, exploiting new technologies and gaining access to formerly inaccessible regions and markets, companies also face increasing threats from existing and new competitors along with a shortage of resources such as materials, energy and skilled workforce. Moreover, the global marketplace is a major driver for customer expectations in terms of lower price level, fast delivery and availability of products that suit whatever needs the customer may have [Pine, 1993], [Ericcson & Erixon, 1999].

In the mass production paradigm product developers' and designers' focus was on optimising the *single* product to limit costs to a minimum. In companies that still operates in the mass production paradigm and tries to serve the market by deriving the demanded product variety it has shown to create complexity in the product family as well as in the production due to the single product focus. In most such companies no one person has the responsibility of coordinating the decisions that are made in the different development projects.

The combination of a market-driven product development strategy and the fact that no one is responsible for the development of the entire product family, will in time lead to a situation where the company is struggling under complexity in the product family [Meyer & Lehnerd, 1997], [Franke et al., 2002]. Initiatives applied on single products such as design for manufacture and assembly (DFMA) are no longer sufficient [Ericcson & Erixon, 1999]. As a consequence there has been an increase in the number of companies that are beginning to change their focus from single products to entire product families.

The challenge of identifying and modelling this internal company complexity in order to make decisions on how to control complexity and cost is the chief background for this research.

1.2.1. Reasons for growing complexity

A challenge faced by many companies is that a growing number of different commercial product variants leads to an aggressive growth in the number of different design concepts, subsystems, components, manufacturing processes and competencies needed in the company to derive the various products.

There are several reasons for this, but the main reasons for this growth of internal diversity are;

- *Changes in markets*
  Growing competition due to a more global market place has increased the customers' (consumers as well as business-to-business) expectations to have products customised to fit their exact need [Pine, 1993].
- *Responsibility of the product range*
  Many companies have a rather liberal stand point when it comes to product range management and product development. The design discipline is often quite loose i.e. the responsibility – if any – for design decisions on a product range level is decentralised [Fiore, 2005].
- *Economic models*
  There is a lack of economic models that support managing the trade-off between differentiation and commonality, i.e. the desire to differentiate the products and the desire to share between the products [Ulrich & Eppinger, 2000]. The evaluation of new designs is based on cost optimisation models seeking to improve the variable cost and not the total costs. Therefore designs are sub optimised and the total costs are rising due to the resulting internal diversity [Meyer & Lehnerd, 1997].
- *Data discipline*
  Data bases and data in general are important and useful if used utilised efficiently. This, however, requires that data such as product information is stored with great discipline. Unfortunately, data discipline is not given proper prioritisation in the daily quest for customers and market shares [Kratochvíl & Carson, 2005], [Fiore, 2005].

Changes in markets

The ongoing globalisation of business and the general rise in living standards is a major driving force in the change of most markets as they become increasingly more diverse.

Customers of today are not very likely to accept Henry Ford's product offering with "any colour as long as it is black". Today's customer wants products that are fitted to meet their exact needs or wishes. This change is true in the consumer markets as well as in the relationship between companies in supply chains.

Consumer markets

Consumers are becoming increasingly aware of the fact that they can express their personality through the products they buy and use – and people want to stand out from the masses and to be regarded as unique individuals [Fiore, 2005]. Therefore it is no longer sufficient to have the same product as your neighbour. Consumers demand products that fit their individual personality - ultimately custom made products but in reality in a trade off with the price level [Pine, 1993].

Business to Business markets

In the B2B markets the large OEM's has increasing focus on optimizing costs and product performance, and they no longer want to pay for functions or performance that are unnecessary in their application. Mass produced off-the-shelf products are normally specified to meet a broader market, which means that a product is often over specified from an OEM point of view. This is a driver for customised products.

Product on demand - from Push to pull

Push strategies have been the norm in the past. Many companies have developed high performance products at the lowest possible price (often through Mass Production) and then pushed their products onto the marketplace without an exact knowledge of customer demands but rather a forecast. This strategy is only cost-effective with a relatively low number of product variants, since it entails relatively high inventory levels for each product variant.

In recent years - and especially since the introduction of Lean manufacturing - the trend has shifted towards a pull strategy, in which companies are beginning to produce and develop products on demand [Fiore, 2005]. To keep down lead time, companies have to have a very flexible setup in order to customise on demand.

Responsibility of the product range

In most companies the product management has a marketing focus, which imposes a strong focus on having the right product and less focus on deriving the products in the most effective way. Consequently, decisions regarding product design are decentralised and left to the individual design engineer. He/she has no responsibility to align design decision across the product range, and is purely measured on the ability to solve the individual design task. Furthermore, designers are inventors by nature and always seek new and better solutions, and they see nothing prestigious in sharing or reusing designs.

In the companies that have been part of this research, similar designs has been developed by different designers without them being aware of the other designer's work – i.e. they have been re-inventing the wheel again and again, and hereby added to the number of designs, sub-assemblies and components without adding any actual value.

Economic models

Business potential is a major issue when managers and/or engineering designers are deciding on new additions to a current product range. What may seem economically profitable from an isolated single product viewpoint is not always the best from a total cost point of view. That is a problem in many companies because many traditional product cost models are based on variable costs and not the total costs i.e. the fixed costs are in fact assumed to be fixed and thus kept out of the analysis.

An optimisation of variable cost alone will – in most cases – lead to a product range that is not designed for variation or a flexible customisation of products. A sub optimised of a product range will lead to redundant functionality in different designs – such differences adds to the complexity without adding customer value.

Sometimes there is a contradiction between variable costs and fixed costs because a reduction in the variable costs may lead to an apparent increase in the fixed costs and thereby the total costs. In the manufacturing industry material use and production lead time often plays a vital role when optimising designs or when making additions to a current product range. A cut down in the material use may lead to components being optimised to very specific purposes. A material optimisation of component X may lead to the fact that a new and different component Y has to be made for a very similar purpose.

Component Y and X become so specific that they are unique to one or few applications. If one of them where "over-specified" slightly that one component might solve both problems. From a variable cost perspective they are both optimised. The problems occur when large numbers of sub optimised parts and components are developed over the years. Each new variant adds to the bill of material, product data, a new shelf space in the production, maybe a new fixture on a production line and so on. The resulting complexity and associated costs are not taken into account in cost models of today. Even in Activity Based Costing models and other attempts to handle the potential rise in fixed costs, it is very hard to determine actual cost of complexity [Bukh & Israelsen, 2004].

Data discipline

All the diversity added due to the above becomes a cost driving complexity mainly because product information is stored with little discipline in terms of e.g. structure and classification. The designer's interest and focus is on solving the design problem – not on documenting the result. This is the phenomenon illustrated in figure 1.1. The designer is focusing on satisfying the customers and developing the demanded product solutions, and this is what he/she is rewarded for – not for carefully and systematically storing the product data documenting the outcome. The product information is stored in the company's various data system (e.g. ERP, PDM, CAD) much like clothes in a pile of laundry (fig. 1.1.).

Figure 1.1. *Some designers sort and structure their data using the same approach as they apply when compiling a pile of laundry at home [Mortensen & Harlou, 2004].*

1.2.2. Complexity as a cost driver

The changes in markets, lack of responsibility for the product range and the inadequate economic models together with the lack of data discipline form an evil circle of growing internal complexity. The amount of data and the way it is stored is a combined problem leading to complexity. Designers may be fast and customer oriented, but if they do not constantly seek to optimise the totality of the product range and to store designs and data in a structured way, complexity will grow uncontrolled and start to weaken the organisation and eventually the business potential of the company.

More complexity makes it harder for engineering designers to maintain an overview of the product range. When a new customer request with a new set of specifications is received it is hard to determine whether it is good or bad business to engage in this new business opportunity. Moreover, it is often hard to say no to the customers as most sales persons and engineers are trained to have it as their prime task to satisfy customer needs. Therefore new designs and additions to the existing portfolio of products may be realised without a profitable business case that supports it.

The result of the complexity is a serious lack of overview among employees in the company. It is hard to find existing designs, hard to determine the possibilities of the product range, hard to give a fast and reliable feed back to customer requests. The lack of overview thus prevents reuse and a large proportion of new customer demands will derive a chain of development activities, parameters changed, new components, bills of materials, documents and the like, even though the extra functionality may be very close to that of existing designs within the range. As the product range becomes more complex reuse becomes even more difficult and the circle of complexity continues.

One of the major aspects that keep most companies trapped in a costly and lifelong relationship with complexity is the limited ability to make decisions at a product range level – partly because of the invisible waste and partly because of the level of knowledge in the management. Many managing directors in marketing, product development and production, do not have a total overview of the product family and do not have enough product knowledge to compensate for this lack of overview. The way information is stored is supporting decision making on a product detail level rather than a product range level. The information is somehow inaccessible to management and other key persons with decision making responsibility for the totality of the product family.

1.2.3. Rationalisation existing products

Companies burdened by complexity are often enticed by initiatives as mass customization, lean production, just-in-time, build-to-order, etc. An important first step before engaging in implementation of such initiatives is to rationalise the products. Failure to do so leads to the industrial equivalent of "pawing the cow paths" [Anderson & Pine, 1998].

When rationalising the products it is important not to have a single product focus. This will only lead to incremental improvements not nearly enough to secure successful implementation of any of the above mentioned. It is necessary to focus on rationalising product families or product families to achieve the needed effects. Unfortunately, only limited tools and methods are available to support making decisions about rationalising product families.

The result is that product committees and project managers engaged in decision making are often forced to base their decisions on a patchwork of details rather than a complete overview of the products.

1.3. The research challenge: "Modelling product families"

The business challenge of growing complexity in product families has created a need for tools that provide guidance on how to improve product families and enable modelling of the complex system of multiple parameters. This need has been addressed by different research methods.

As mentioned earlier literature provide several economic models to measure the performance of a product family [Meyer & Lehnerd, 1997]. However, these measures can only be used to indicate whether the product family is doing well or not – something the company would probably have a certain feeling of on beforehand.

There has been made some research on commonality indices for evaluation of product families [Thevenot & Simpson, 2004], [Martin & Ishii, 1997]. These indices basically focus on a comparison of the physical components of different products in a product family.

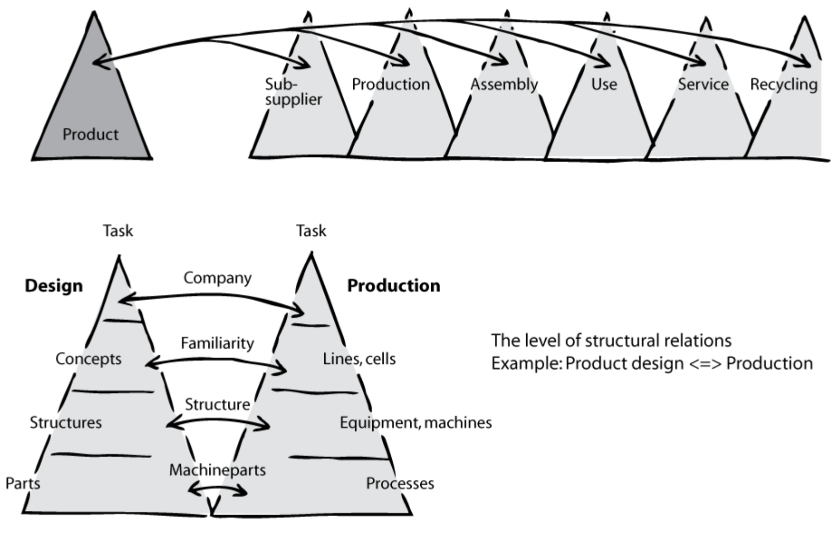

Figure 1.2. *Relations between the product and structures related to the product life determine how well the product will perform in the "meeting" with the product life system. The levels of structural relations are exemplified using product and production structures [Andreasen et al., 2001].*

Otto and Hölttä-Otto [2007] presents a technique based on multi-criteria evaluation. This method has 6 indicator scores (complexity, customer, flexibility, organization, variety and after sales) representing different views on the product family.

However, none of the above performance measures indicate *why* the product family is performing well or, maybe more importantly, why it is not doing well, if that's the case.

According to the theory of dispositions [Olesen, 1992] the fit between the product design and the product life systems determines the overall performance of the product throughout the entire life cycle. The product design and the life phase system should be fitted to each other and/or designed concurrently to achieve the optimum performance.

In relation to effective development and production of product variety, research on product platforms and mass customization cannot be overlooked. The above proclamation on dispositions suits well to describe the objective of such engagements as a means to effectively create the needed product variety. That is, development of a product platform can be regarded as preparing the creation of product variants by fitting the product structure especially to the structure of the production setup and supply chain in general. This fitting activity is referred to as alignment [Andreasen et al., 2004], [Andreasen et al., 2001], [Ericsson & Erixon, 1999]. How well the relevant structures are aligned determine how friction-free development and production of new product variants will be (fig. 1.2.).

Hence relations between the products and different product life systems become very interesting to study when examining a product family's state regarding the ability to offer the necessary product variants effectively and efficiently. Again, it is the relations between the product structure and the product life systems related to the supply chain that are of prime interest.

The challenge from a research point of view is to make these relations visible (i.e. to model these relations) in order to study them. Yet, little literature is concerned with the modelling and visualisation of such relations, and especially not in connection to product variety and product families.

Figure 1.3. from Andreasen et al. [1996] illustrates the research task very well. On the left hand side variety in the product family is illustrated using the chromosome model [Ferreirinha et al., 1990]. On the right hand side the product life phases and coherent life phase systems are illustrated. Modelling the interrelations (arrows) between the two is exactly the objective for this research. According to Andreasen et al. [1996] four principle types of variety may exist in a company's product family. That is, variety at process, effect/function, organ and part level in accordance to the domain theory [Andreasen, 1980].

Unfortunately, the figure only illustrates the issue of dispositions related to product variety. No examples of actual practical application are found in the literature. This research will develop a model based on figure 1.3. and attempt to apply this model in an industrial setting.

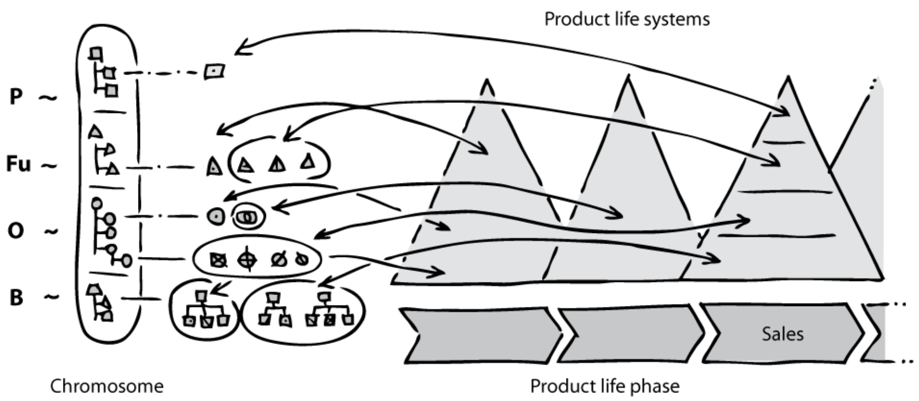

Figure 1.3. *Relations between variety in the product family and the product life activities. The product family is modelled using the chromosome model [Ferreirinha et al., 1990]. Four types of variance seem to exist: variance at process (P), effect/function (Fu), organ (O) and part (B) [Andreasen et al., 1996].*

Harlou [2006] introduced the so-called *Product Family Master Plan* (PFMP) (see section '6.3. PFMP') as a modelling tool to describe the structure of the product family and variety within the product family. In short, the PFMP is a modelling tool based on the domain theory [Andreasen, 1980] and the comprehension from Andreasen et al. [1996] that several viewpoints are needed to describe a product or product family. Though, the PFMP only has three views (customer, engineering and part view) - and not four – the views are comparable to the four domains in the domain theory. Furthermore, the PFMP has already proven its worth in industrial applications as an assessment tool when designing or re-designing product families [Mortensen et al., 2008 (a) & (b)], [Harlou, 2006].

It is said, that pictures are worth more than a thousand words. If we bear in mind that the aim is to support industrial companies in getting an overview of an often very complex situation, the focus of this research is on *visual* models [McKim, 1980]. Also, it seems that the ability to visually present an overview of the variety in the product family and the interrelations between the three views is what makes the PFMP a valuable tool. Creating the wardrobe illustrated in figure 1.4., which serve as a metaphor for this visual model can be interpreted as the basic research challenge.

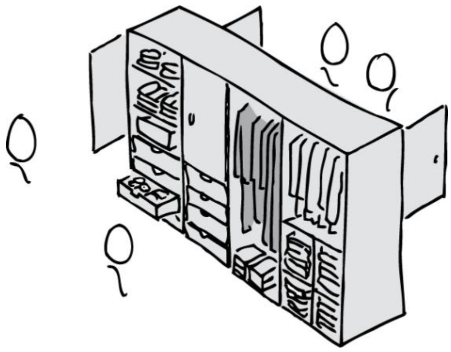

Figure 1.4. *Visual modelling of a product family can be compared to structuring the clothes from a pile of laundry in a wardrobe in order to get a better overview [Mortensen & Harlou, 2004].*

Extending the PFMP tool with the intention to model and visualise the relations and "the fit" between the product structure and other life phase systems is the focal research objective for the work presented in this thesis.

1.4. Response to the challenge

One of the key assumptions in this research is that design teams in industry need a stronger set of models to visualise and communicate the totality of a complex mature product range in order to make well-founded decisions about redesign of the product range as part of a business strategy towards mass customization. Such tools should not only support the work of the design team and their understanding of the challenge, but also document the arguments behind the design solution and support communication of them to outsiders, e.g. management.

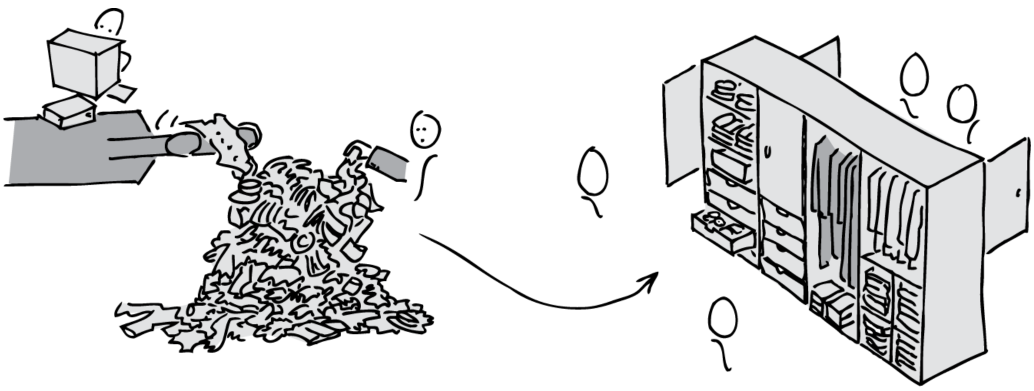

Figure 1.5. *Years of product development and poor data discipline where product information is stored much like the clothes in a pile of laundry will in time leave the company in a situation where decision-making about the product family becomes very difficult. The aim of this research is to model product families in a structured way (similarly to the way a wardrobe presents the clothes) in order to give a better overview of the possibilities, faults and imperfections in the family [Mortensen & Harlou, 2004].*

The academic literature does not provide readily applicable solutions, but only indications of what such a solution should feature.

The objective of this tool can be illustrated by combining figure 1.1. and 1.4. If the clothes is presented in a structured way - like in a closet – it gives a better overview of the wardrobe and serves as a better foundation for making decision about what to wear, what to buy or what to throw away (fig. 1.5.). Similarly, presenting information about the product range in a structured way should serve a better foundation to make decisions about what can be used to meet certain specifications, what new should be developed to close gaps in the product range, and finally what could be removed from the product range.

To summarise the objective, this research should;

- Present an overview of a product family in order to support decision-making at product family level related to re-design of the products
- Develop an understanding of what elements are relevant to study in the diagnosis of a product families performance regarding effective creation of value-adding product variety
- Model relations between product variety in a product family and product life systems related to the supply chain
- Test the resulting research results (i.e. the model) in at least one industrial case study to prove its applicability and worth

1.5. Research questions

Based on the above introduction the following research questions have been formulated for this research work;

Research question 1

What information and data elements – especially about product design and production setup - are required in the assessment of a product family's performance regarding effective and efficient production of value-adding product variety, and what elements should then consequently be taken into account when re-considering the design of the products in the product family and/or the coherent production setup?

Research question 2

How can these different types of information and data elements (research question1) be refined and presented in way that it links the various types of information and data in order to visualise relations between the products' design and life phase systems related to the production and supply chain – providing the necessary details and, yet, still maintain the overview in order to support and improve decision-making related re-design of the products in a product family and/or the coherent productions setup?

1.6. Structure of thesis

This section is attempt to explain the structure of the thesis and the argumentation that lie behind the chosen structure, and hereby guide the reader through the research work presented in this thesis.

As illustrated in figure 1.6. the thesis is divided in 8 parts. Although, the actual research work has not been a sequential stepwise process reflecting the 8 parts, the thesis is structured in this way because it is considered more reader-friendly.

Part 1 presents an introduction to the research that is reported on in this thesis. Part 1 describes the business challenge of uncontrollable growth of product complexity, as well as the research challenge of modelling product families, which form the background of this research work. Concluding, part 1 presents two research questions that are to be answered in the research work at hand.

The objective of Part 2 is to present the scientific approach used in the research work that is presented in this thesis. Part 2 includes a description of the research objectives, the research object, the research methods that are used and the design of the research. Finally, Part 2 includes a discussion of the strategy used for verification and validation of the research work presented in this thesis.

The objective of part 3 is to present the theoretical basis upon which the research work is founded. Part 3 will go through a series of different research fields and disciplines, and describe why they are relevant to the research work presented in this thesis. The frame of reference presented here in part 3 has deliberately been separated from a review of state-of-the-art product family assessment tools and methods, which are presented in part 5. That is, part 5 presents a review of methods and tools that directly address the requirements established in part 4, whereas part 3 include a review of a broader and more fundamental body of knowledge. Nevertheless, some overlaps between part 3 and 5 do occur.

Part 4 of the thesis has the objective of presenting the requirements for the developed support that is to be used for assessing product families. That is, the findings in the descriptive study (I) in the form of a reference model, plus the additional experiences made in the subsequent prescriptive work. Finally, the identified requirements are described in detail to serve as guidance for the development of the tool and as benchmark for the concluding evaluation of the tool.

The objective of Part 5 is to present the current state-of-the-art product family assessment tools and methods that are presented in literature. The methods and tools are review with respect to the requirements that were established in the Part 4 and with the intension of identifying methods and tools or elements of these that could contribute to the support developed in this research work.

Part 6 introduces the developed modelling formalism that can support decision-making in the process of re-designing the products in a product family with a view to make production of the needed product variety more efficient/effective.

Part 7 reports the experience from applying the research in an industrial case. The tool has been used to analyse a product family of solenoid valves at the company Danfoss AC.

The objective of part 8 is to recapitulate the results of the research work including giving answer to the research questions that were formulated at the beginning of the research and summing up the contribution from this research work. Part 8 also elaborates on the experiences that were made during the practical implementation of the research results at the case company Danfoss AC and the limitations of the developed support. Finally, part 8 point out areas for future research.

The progress of the research work has been rather iterative. This is illustrated by the arrows in figure 1.6. that represent that the research work presented in one part either contributes to the work presented in another (super- or subsequent) part or brings answer to questions raised in a previous part.

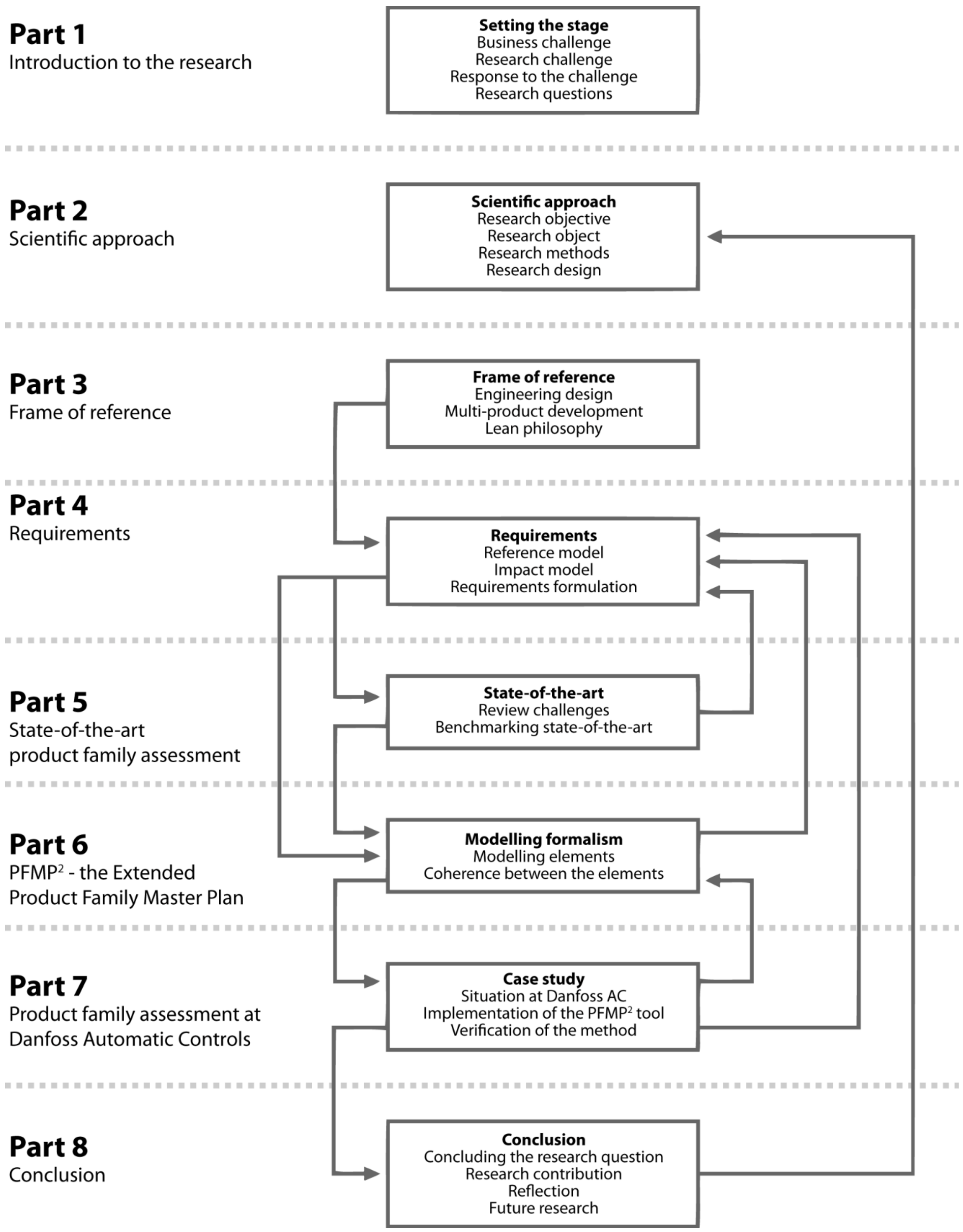

Figure 1.6. *Structure of thesis. The thesis is divided into 8 parts. The arrows represent iterations in the research work, i.e. that research work presented in one part either contributes to the work presented in another (super- or subsequent) part or brings answer to questions raised in a previous part.*

Part 2

Scientific approach

The objective of Part 2 is to present the scientific approach used in the research work that is presented in this thesis. Part 2 includes a description of the research objective, the research object, the research methods that are used and the design of the research. Finally, Part 2 includes a discussion of the strategy used for verification and validation of the research work presented in this thesis.

2.1. Research objective

This research detains to the field of applied research, i.e. the research is focused on practical applicability of the research results. According to Ropohl [1971] such research has two objectives: (a) a practical objective and (b) a theoretical objective, of which the theoretical objective serves primarily as a means to reach the practical objective.

In the following the research objective is divided into a main research objective plus three sub-objectives. The main objective can be characterised as a practical objectives whereas the sub-objectives are of more theoretical nature and serve as means to full fill the main objective.

Main objective

The main objective of the research can basically be formulated as the following;

> ***Main objective***
>
> Develop a construct that can support designers when analysing and diagnosing a product family by establishing a visual overview of the products and hereby support decision-making about re-design of the products with the intention to minimise complexity and improve the ability to derive the demanded product variety effectively.

Sub-objective 1

A fundamental understanding of what and how different factors influence the ability to derive product variety effectively - and how they are related to each other - is evidently necessary in order to focus the research and address the factors that are most likely to contribute to success of the project (i.e. achieve the main objective).

Hence sub-objective 1;

> ***Sub-objective 1***
>
> Develop an understanding of what elements are relevant to study in the diagnosis of a product family's performance with regards to effective creation of value-adding product variety

Sub-objective 1 should be achieved through the work done in the descriptive study (I) described in section 'Descriptive study I'.

Sub-objective 2

Andreasen et al. (2001) argues that the relations between the product and structures related to the product life determine how well the product will perform in the "meeting" with the product life system. It is assumed that a better understanding can be achieved via an explicit visual modelling of these relations, and that this understanding can support decision-making in a re-design process.

Hence sub-objective 2;

Sub-objective 2

Model explicitly relations between product variety in a product family and product life systems related to the supply chain

Because this research deals with effective creation and production of product variety focus will be on modelling the relations between the products and product life systems related to the production and the supply chain in general.

Sub-objective 2 is addressed in the prescriptive study described in section '2.5.3. Prescriptive study'.

Sub-objective 3

Verification of the research results is indisputable. In this study however the practical applicability of the research results is considered of utmost importance. Hence, it is of high priority to undertake a study in real circumstances – i.e. in an industrial company.

Hence sub-objective 3;

Sub-objective 3

Test the research results in real circumstances (i.e. in at least one industrial case study) to prove its applicability and worth

Ideally, sub-objective 3 should be addressed in a detailed descriptive study (II). In practice it is not possible to set up a large scale test in which the findings of the research can be evaluated. Instead the practical applicability and worth of the research results will rely on statements from selected persons from industry (and academia). This part of the work is described in section 'Descriptive study II Descriptive study II'.

2.2. Research object

When designing the research project it is important to distinguish between the research objective (the expected results of the project) and the research object (the phenomenon you wish to study)[Ropohl, 1997].

In accordance to the perception that the interaction between the products and the production setup is decisive for the ability to produce the variety of products effectively, the key scientific research object is;

Research object

Relations between the product family and other product life systems related to the production and the supply chain in general

A better understanding of the relevant relations must be critical to making better decisions for the purpose of aligning the design of the products and the design of the production.

2.2.1. Limitations

The research is limited to focus on a certain type of business and the related nature of such business' product families, which are described in the following.

This follows the presumption that many companies in this specific situation are the companies that are burdened by the challenge of growing product complexity. These companies are therefore also the ones that can potentially benefit from making decisions about alignment between the product structure and production system at product family level [Sanchez, 1999], [Harlou, 2006].

Accordingly, this research is directed at such companies and appurtenant product families, which is illustrated in figure 2.1. The three axes; (a) Product volume, (b) Product variety and (c) Product complexity form a cube that can be used to describe the nature of a product family.

The scope of the research, i.e. the nature of product families in which this research is relevant, is described by the smaller cube in the centre. That is, average product volume, average product variety and average product complexity.

If the average volume of the product variants in the product family exceeds a certain level then principles of mass production becomes applicable and the cost-optimisation of the production should be made at product level – not product family level. If the volume deceed a certain level the business simply becomes uninteresting (depending on product margins, which is somewhat related to the complexity of the products).

Concerning product complexity this research basically does not deal with one-of-a-kind products (e.g. ships). In that case, the product's relations to other life phase systems than production become more relevant to study (e.g. the design phase). At the other end, production of nails, bolts, nuts or such simple products (seen from a design point of view) are outside the scope of this research. Such products are normally mass produced and analysis at product family level again becomes uninteresting.

Finally, the level of difference in the products plays a role. Even though it is imaginable that the same company has televisions and vacuum cleaners in their product assortment it is not the intention of this research to deal with product variety of this extend. On the other hand a certain level of product variety is expected in order to cause the earlier mentioned complexity and thereby making this research relevant.

Bear in mind that figure 2.1. serves primarily as a mindset used to describe the scope and no explicit limits are meaningful.

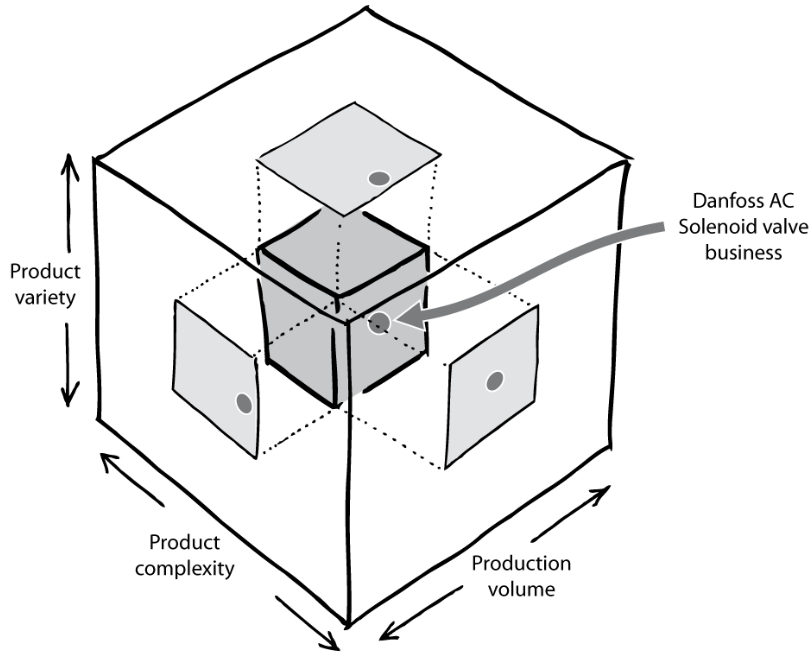

Figure 2.1. *Product families that lies within the scope of this research have average product complexity, average volume and average product variety. This is illustrated by the smaller cube in the centre. The nature of the product family from the Danfoss AC case study that is used in this research is indicated by the black dot.*

2.2.2. Case selection: Danfoss Automatic Controls Solenoid Valves

To apply the research, the company Danfoss AC was selected, specifically the solenoid valve business, because it fulfilled the above characteristics. The case can be described in the cubic framework and give an impression of what is inside the cube.

Danfoss AC is a so-called component supplier. They provide mechanical and electrical products and components to OEM customers and wholesalers. The solenoid valve business which is used as primary source in this research has 230 product variants in the product family sealing from 1 to nearly 160.000 pcs. pr. year pr. variant – averaging 7.500 pcs. pr. year pr. variant (only approximately 100 product variants sell more than 1.000 pcs. pr. year).

Regarding volume and product variety this fits perfectly into the centre of the scope. Concerning product complexity the solenoid valves rarely consist of more than 50 physical components (sometimes as low as 10 components). This is properly in the lower end of what product complexity is needed to make this research relevant.

2.3. Research methods

The approach used in this research cannot be described as one single design research methodology, but rather as sub-sets of various available approaches. The methodologies described in the following sections have formed the basis of this research methodology framework.

2.3.1. Applied research

The research reported in this thesis has its starting point in a practical problem and accordingly a phenomenon in industry and literature is analysed and diagnosed. The research is primarily conducted in an industrial setting, meaning that the research deals with the problems as they are perceived in the organisational setting. Consequently, these problems must be subjected to a more formalised and scientific framework.

The illustration by Jørgensen [1992] in figure 2.2. presents a method to address the interplay between the practical and theoretical work in applied research.

As problem areas are discovered in the industrial setting they are analysed in the context of the theoretical basis, whereupon theoretical hypotheses and problems are formulated. The solutions developed to address these problems must be subjected to evaluation and critique from practitioners as well as the academic community to check their validity and applicability. Thus, the solutions are applied under real circumstances, i.e. in the industrial setting or other test cases and examples.

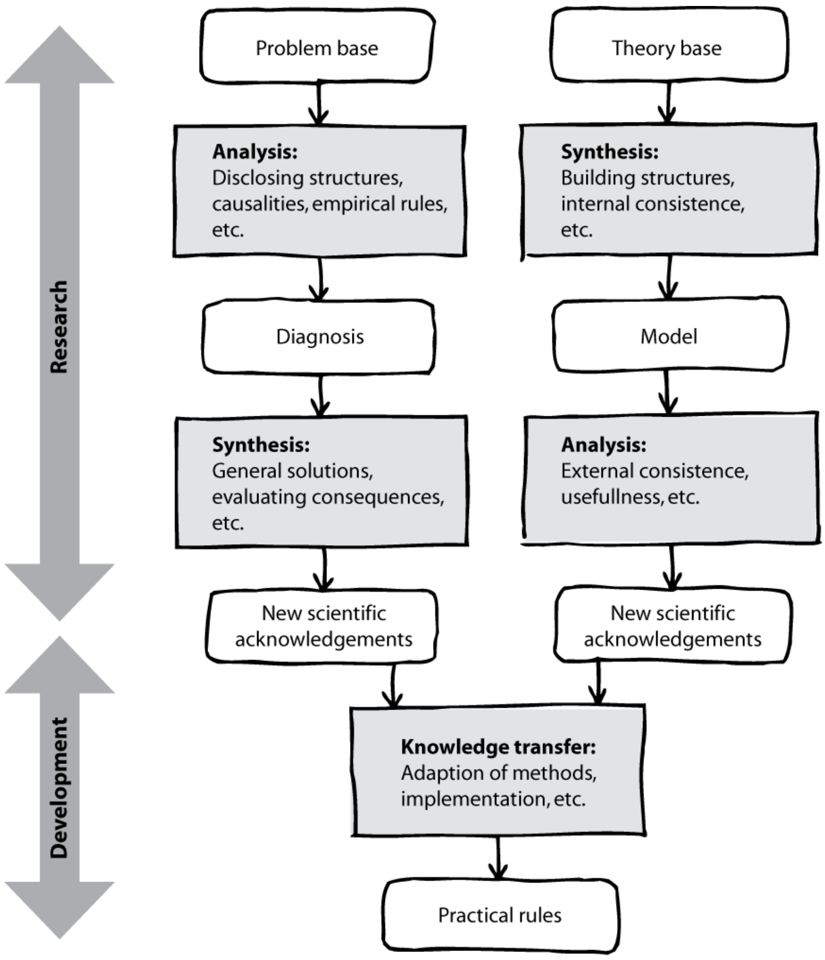

Figure 2.2. *A method to address the interplay between the practical and theoretical work in applied research [Jørgensen, 1992].*

2.3.2. Action research

Action research is concerned with the study of phenomena's that would not have occurred without the researcher's influence [Coghlan, 2007]. In action research it is difficult to distinguish clearly between first a descriptive and then a prescriptive phase. Rather the research is part of a progress where the experience and knowledge acquired are the research results.

Although, the research approach described in the subsequent section '2.5. Research design' has clearly defined descriptive and prescriptive studies realities are that the practical execution of the studies has been much more blurred, meaning that after a preliminary descriptive study (as described in '2.5.2. Descriptive study I') the research has been switching back and forth from being of a prescriptive and descriptive nature, respectively.

This approach has been used to benefit as much as possible from the industrial collaboration, because it is believed that several iterations foster better results in the form of a better method.

2.3.3. Case study

The case study [Yin, 1994] as a research methodology allows the researcher to study the phenomenon in real circumstances. On the other hand it can be difficult to state general conclusion based on a case study. As research methodology the case study resembles action research, with the exception that the case study does not imply interference by the researcher, though it can be difficult to avoid since the mere presence of the researcher can lead to changed behaviour of the involved.

2.3.4. Engineering design research framework

The research follows the approach described in the framework set up by Blessing & Chakrabarti [2002]. The framework illustrated in figure 2.3. describes a process beginning at formulating the success criteria (aim) of the research. Next step is to study the object and through observation and analysis get an understanding of the factors that influence the success criteria (description I). This understanding enables the research to prescribe actions (e.g. methods) to address the influencing factors in the desired direction (prescription). Finally the effects of the prescribed methods are observed and analysed (description II). The knowledge gained in this process can then be used to evaluate and either validate or improve the initial description and prescribed actions.

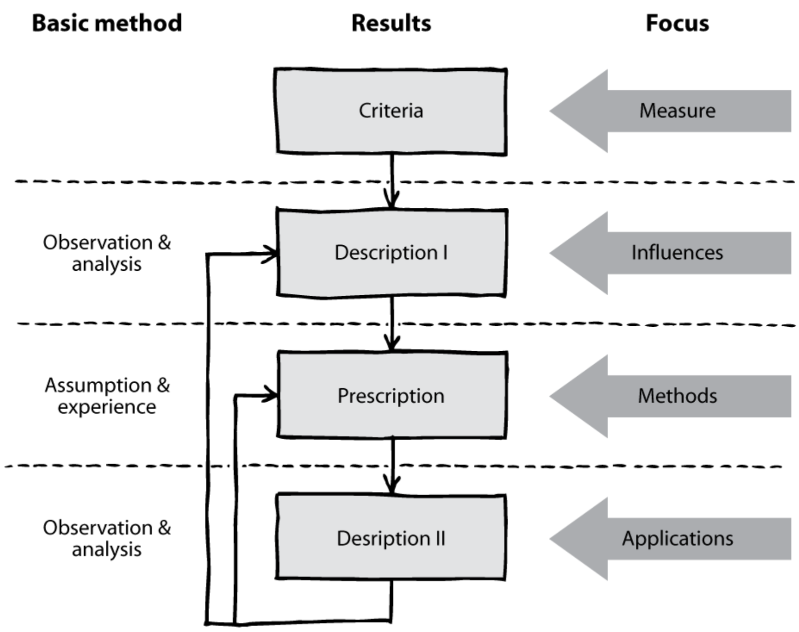

Figure 2.3. *Engineering design research framework [Blessing & Chakrabarti, 2002] proposes the following steps in design research: (a) criteria formulation to establish a measure to determine whether the research has been successful or not; (b) an introductory descriptive study (I) to establish an understanding of how the success criteria can be influenced; (c) a prescriptive study to address the problem by the use of new methods; (d) a concluding descriptive study to evaluate the application of the developed methods.*

2.4. Research verification and validation

Any research study will involve the researcher at some point. And any involvement of the researcher will affect the study and the conclusions of the study. The researcher may affect the findings and the interpretations of those findings. Same thing applies for the conclusions based on a literature review as the choice and mix of references, along with the interpretation of them will rely on the researcher and his or her background and frame of reference, no matter how objective and unbiased he or she will try to conduct the work.

If the study is of a rather quantitative nature one may be able to use experimental design setups that allows the researcher to rule out his own influence and other interdependencies using statistical methods to deal with data [Montgomery, 2005], yet there is no guarantee that one will succeed. If the study is of a more qualitative nature one may experience a much more blurred set of inputs and outputs. Consequently, the conclusions are potentially harder to make on an unbiased foundation.

Different types of studies and research topics will result in different levels of research participation and involvement. This study has two major potential drawbacks in terms of verification and validation due to the research setup and partly due to the research field, as engineering design research is often rather hard to make quantitative:

- The study is performed using action research meaning that the researcher takes an active part in the work. This makes it a non trivial task to directly infer about the use of the research results in situations without the presence of the researcher.
- The conclusions from the study are based on a single case from one company and one project.

This implies some constraints on the ability to verify and validate the work under study. There are different ways to go about that issue [Pedersen et. al, 2000], [Yin, 1994], and they are discussed in the following.

2.4.1. The validation square

The problem of validating an engineering design research study is discussed by Pedersen et al. [2000]. They discuss a framework for validating design methods. The aim of this research is not directly to prescribe a design method rather the desired result of the research is to provide a modelling method useful for product designers and decision makers. It seems fair then, to use the framework and mindsets related to the evaluation of design methods, and conduct a use a similar approach to evaluate the confidence in a modelling method.

Pedersen et al. [2000] argue that a method may hold four types of validity, and see validity as confidence in usefulness. The differences in these four types of validity are spanned by theory versus empery and structure versus performance as seen in figure 2.8.

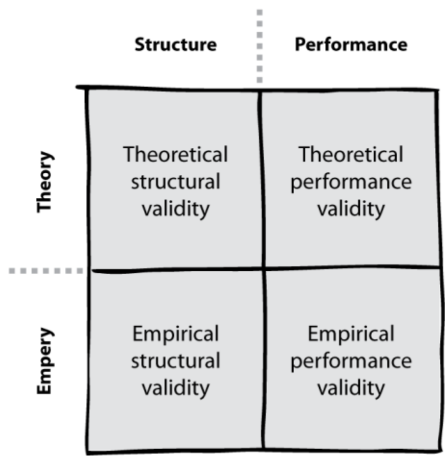

Figure 2.8. *The validation Square has two dimensions of variety. Theory versus empery and structure versus performance. Adopted from Pedersen et al. [2000].*

Figure 2.8. gives a representation of the four types of validity:

- *Theoretically*
  Validity may of a method be supported *theoretically*, usually arising from the results of other studies, e.g. if the method is based on existing and well accepted research such as several peer reviewed journal articles with a high citation index.
- *Empirically*
  Validity of a method may be supported *empirically* if there is empirical evidence to proof the research, i.e. data and results from tests, interviews, etc.
- *Structure*
  The validity of a method may relate to the *structure* of a research result, i.e. the internal logic of the method is sound.
- *Performance*
  The validity of a method may relate to the *performance* of the method i.e. if the method has an effect.

Figure 2.9. is an elaboration of the validation square showing a framework for the use of the square. Pedersen et al. [2000] argue that the structural validation is of a qualitative kind relating it to the effectiveness of a method. Structural aspects are not easy to quantify and measure as they have to do with the internal consistency of the method, thus being qualitative. Consequently, they argue that the performance validation is of a quantitative kind and that is has to do with the effectiveness of a method.

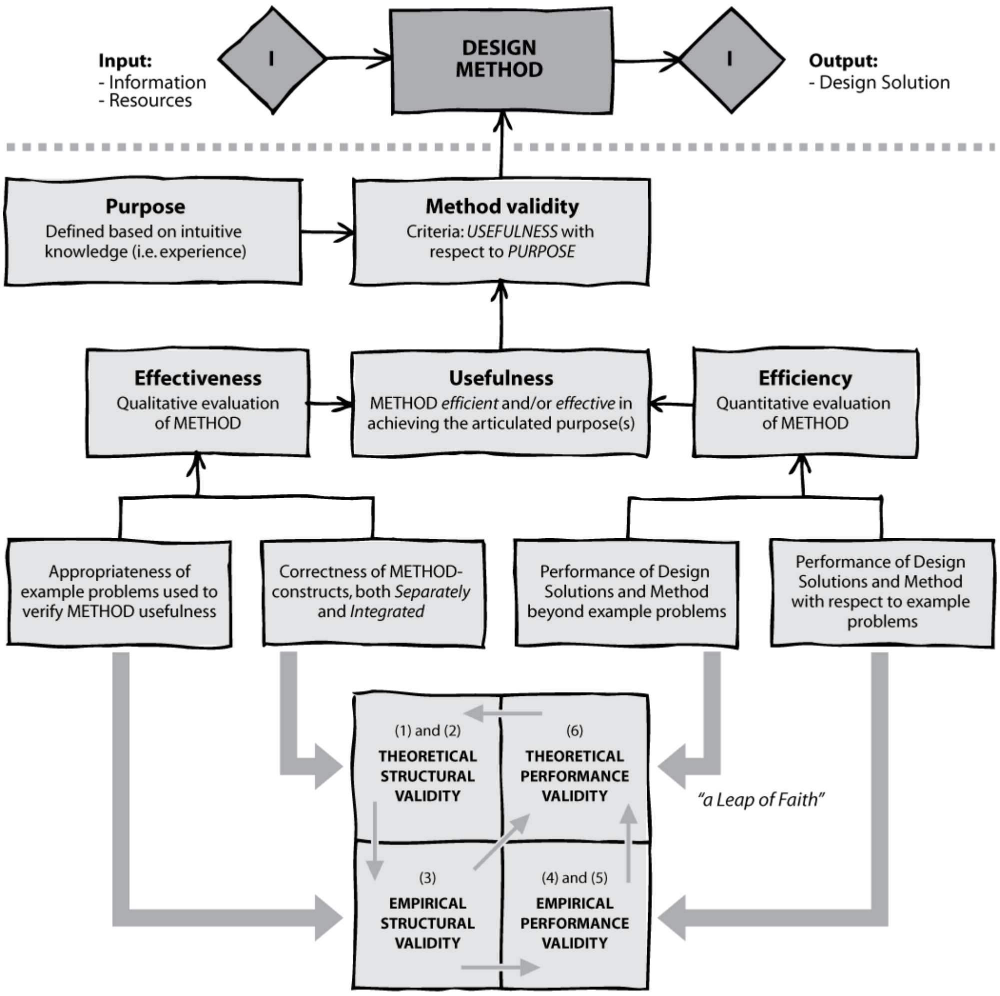

Figure 2.9. *The Validation Square framework. The square itself is placed in the bottom of the figure. The numbers in square refers to different validation steps. These steps are described in the following text.*

Using the validation square to validate a method is the task of proofing that the method complies confidently with some or all of the four types of validity. Six steps are defined;

1. Accepting the construct's validity
2. Accepting method consistency
3. Accepting the example problems
4. Accepting usefulness of method for some example problems
5. Accepting that usefulness is linked to applying the method
6. Accepting usefulness of method beyond example problems.

The optimum research validity is of course obtained if all six steps are satisfied. The research in this thesis builds on a single case study. The theoretical structural validity is based on a logic adopted from literature and a preliminary study. The empirical structural validity comes from the case study, thus it only deals with the soundness of the structure in that particular case or in situations that are similar. The foundation becomes shallower when we get to the performance of the research, as the quantitative part of the validation is sparser. The research is demonstrated and represented using another product, than that of the actual case study (In part 5 a bicycle is used to show the ability of the research results), and again the case is used to proof the worth of the research in a real application – yet only a single case. Finally, the usefulness of the research in broader range of companies and product rely solely on a theoretical reasoning.

2.4.2. Case study validity aspects

The social science field has many similarities to that of engineering design research – some might even claim engineering design to be a social and cognitive task, as it is a creative process conducted by human beings. I will not engage in a discussion of the nature of engineering design research and the relations to social sciences. It is sufficient to note that engineering design research and social sciences have two important things in common;

- Both research fields have studies and topics that may be relatively hard to quantify
- Both research fields have topics that have to rely on case studies because the effects under study cannot be replicated in a laboratory

Yin [1994] provides a framework for constructing case studies with validity. He describes four types of tests that are common to all social science methods:

- *Construct validity*
  Establish correct operational measures for the concepts being studied
- *Internal validity*
  Establish a causal relationship, whereby certain conditions are shown to lead to other conditions as distinguished from spurious relationships
- *External validity*
  Establish the domain to which a study's findings can be generalised
- *Reliability*
  Demonstrating that the operations of a study – such that the data collection procedures can be repeated, with the same results.

Internal validity is not used for descriptive or exploratory studies but for explanatory or causal studies only).

Figure 2.10.shows four case study tactics, with the purpose of gaining validity, i.e. confidence in the case study results.

Tests	Case study tactics	Phase of research in which tactic occurs
Construct validity	- Use multiple sources of evidence - Establish chain of evidence - Have key informants review draft case study report	- Data collection - Data collection - Composition
Internal validity	- Do pattern matching - Do explanation building - Do time-series analysis	- Data analysis - Data analysis - Data analysis
External validity	- Use replication logic in multiple case studies	- Research design
Reliability	- Use case study protocol - Develop case study data base	- Data collection - Data collection

Figure 2.10. *Different case study tactics for four design tests.*

Clearly there are differences from an engineering design research study and a social science study. Some of the tactics in the above figure seem more suitable for e.g. a field study of an indigenous population in rural area than testing the worth of a method. But the four tests are very similar to the validation aspects of the four corners of the validation square, and some of the subsequent case study tactics relate very well to the kind of research presented in this thesis.

2.4.3. Verification by logic and acceptance

Buur [1990] suggests two approaches to verification of design theory. It fits very well with the validation square and the idea of internal/external validity in the above figure 2.10. and the framework seems fully applicable for methods as well as theory. The approach is based on the following two aspects:

Logical verification

- A theory has to be *consistent*, i.e. without internal conflicts between the constituents of the theory
- A theory has to be *complete*, i.e. holding the ability to explain or reject observed phenomena of relevance
- A theory has to *support* established and widely accepted *methods* as well as specific *design problems*

Verification by acceptance

- A theory has to be *accepted* by a relevant *scientific community*
- A theory has to be accepted by industrial practitioners

This research does not formulate a theory. The results are more applicable and practical. However, the above bullets are still relevant to the development of a method, even the method in some cases are of a different nature than a theory and therefore cannot be used to explain a phenomenon.

2.4.4. Five evaluation aspects

Olesen [1992] further elaborates on Buur's [1990] thoughts on verification. Olesen [1992] suggests five aspects to have in mind when evaluating research results;

- *Internal logic*
  A research result is internally logic when there is a consistency between the research motivation, the hypothesis and the research results. Moreover, the research has to comply with known theory that is accepted..

- *Truth*
  A research result has truth when the theoretical and practical aspects of the result can be used to explain phenomenon founded in reality and not just theory.
- *Acceptance*
  That is, acceptance by research community and industrial practitioners.
- *Applicability*
  The research results have to be applicable in real problems and cases.
- *Novelty value*
  The research results have a novelty if it includes new results and new approaches.

The idea of *internal* logic and consistency as well as *external* acceptance by a research community and industrial practitioners seem to be a general pattern.

2.5. Research design

The design of the research thesis is based on the described approaches and methods, and uses particularly the Engineering Design Framework [Blessing & Chakrabarti, 2002]. Several types of design research can be derived from the model in figure 2.3. depending on what steps are carried out and how the steps are carried out.

The model for this research project is illustrated in figure 2.4.

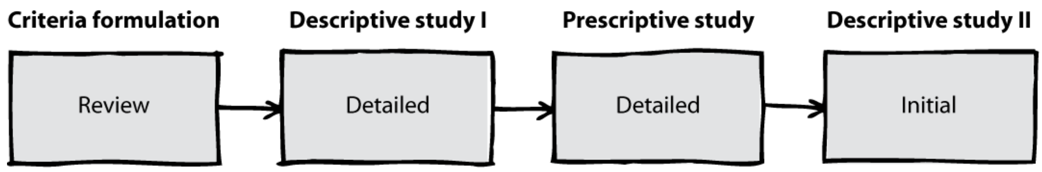

Figure 2.4. *The model for this research based on the engineering design research framework [Blessing & Chakrabarti, 2002] consist of review-based criteria formulation, detailed descriptive study (I) and prescriptive study, plus an initial descriptive study (II)*

This model is chosen in order to accommodate the research and the bearing industrial case in the best possible way. How the steps were carried out is described in further detail in the following sections

2.5.1. Criteria formulation

The purpose of establishing the success criteria for the research is to;

- Identify the aim of the research
- Focus the descriptive study (I) on identifying the factors that influence the success of the research
- Focus the prescriptive study (II) on addressing the factors that influence the criteria most
- Set a benchmark for evaluation in the descriptive study (II)

Blessing & Chakrabarti [2002] distinguish between *success* criteria, which refer to the overall aim of the research, and *measurable* criteria, which translate the overall aim into a criterion that can be used to determine whether the aim is achieved or not.

The success criteria as well as the measurable criteria should be in concordance with the research objective formulated in section '2.1. Research objective'

Ultimately, the aim of this research is to improve the ability to derive product variety effectively.

> ***Success criteria***
> Effective and efficient production of product variety

Although there are ways to measure effectiveness/efficiency it not feasible to expect a measurable impact within the time frame of this research work, why it is necessary to translate this criterion into something more measurable.

Ideally, the link between the success criteria and the measurable criteria should be as direct and as strong as possible and, preferably, it should be based on a review of literature.

In accordance to Andreasen et al. [2001] the relations between the product and structures related to the product life determine how well the product will perform in the "meeting" with the product life system, i.e. the relations between the product and production determine how effectively the product can be produced. Alignment of these relations is referred to as creating of "fit" between the product structure and the production. A better "fit" enables more effective production of the products. Measuring the "fit" or alignment is not a workable criterion for the research either.

It is a fair assumption that the genesis of proper alignment relies on the quality of the decisions that are made about the products at product family level rather than at single product level [O'Connor & Hardenbrook, 2005]. Especially, in the light of the experience that isolated focus on optimisation of single products and production of these is one of the main circumstances that lead to burdening complexity.

It is evidently not an easily measurable criterion to measure the quality or "goodness" of decisions. Such decisions could have an incubation period of many years before they have been fully implemented and the subsequent impacts become visible. Furthermore, studying the impact of the decisions to conclude on the decision quality is not practicable since other initiatives in the company could easily interfere, and make it virtually impossible to argue whether improvements are the results of better decisions about the product family or they are due to other initiatives. Consequently, a more tangible criterion is needed for evaluation of the research results.

Generally, decisions are reliant on the foundation on which they are based – i.e. the better the decision foundation the better are the chances of making good decisions. Bross [1953] mention that decision-making does not rely on raw data – it operates on rather highly refined information/data. Unless considerable care is devoted to the process of refining data it will inhibit efficient decision-making. This is also valid for decisions about a product family.

Figure 2.5. illustrate the link between the success criteria and the measurable criteria. Bear in mind that other factors can possibly influence one more of the criteria in the model (e.g. the amount resources invested in production equipment could presumably have an influence on the production effectiveness/efficiency).

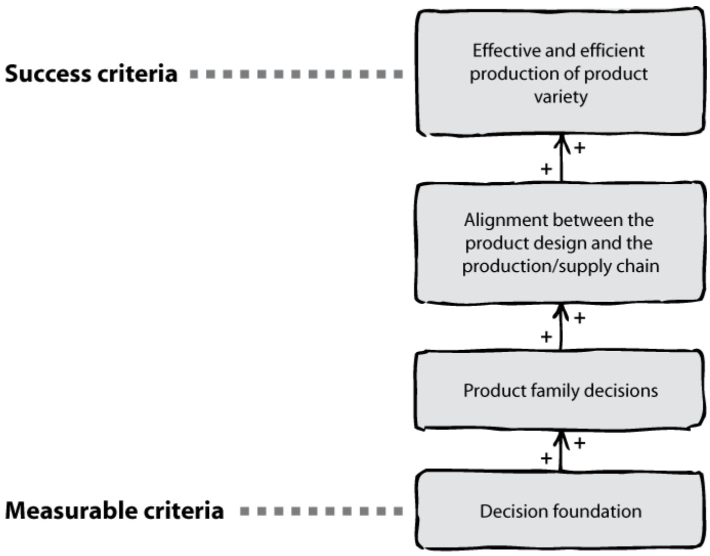

Figure 2.5. *The overall success criterion ('effective and efficient production of product variety') for the research work is transformed into a measurable criterion formulated as: 'decision foundation'.*

Although it is somewhat an exaggeration to declare 'decision foundation' as readily measurable it is a viable alternative to measuring the quality of the decisions, although the assessment of the research results will rely on opinions and perceptions of the intended users of the results.

Measurable criteria

Decision foundation

Since the research is primarily based on a single case study (i.e. the same test persons are repeaters throughout the progress of the research) it is critical for the validity of the research to be observant that the prescriptive study does not only address the needs directly formulated by the test persons, but instead address issues observed by the researcher in the descriptive study (II) and therefore not polluted by the opinions of the test persons.

2.5.2. Descriptive study I

The aim of the descriptive study (I) is to understand which factors directly or indirectly influence the measurable criteria. This understanding is necessary in order to influence the criteria in a desirable direction.

In relation to this research the existing literature on modelling of product families is very limited and it is found insufficient to base the descriptive study (I) solely on a review of literature. Nonetheless, chapter 5.2. presents a review of state-of-the-art literature on the related subject. Since the literature does not provide enough detail, a descriptive study was undertaken based on case studies on industrial application of the initial PFMP tool presented by Harlou [2006] and interviews of consultants with relation to the research group, which have experience in the use of the PFMP tool.

The industrial case in the descriptive study (I) formed a part of a pre-project at Danfoss AC which should clarify the potential for re-design of Danfoss AC's solenoid valve product family.

In practice I as a researcher together with another research colleague had responsibility for the pre-project and the implementation of the PFMP tool, with the help of designers at Danfoss to provide the necessary data and make recurrent reviews of the PFMP for the Danfoss AC solenoid valve products.

The implementation of the PFMP tool should bring forward an understanding of how such a tool can support decision-making by modelling a product family from various view points. Furthermore the study should reveal current inadequacies or improvement potentials of the PFMP tool, which can targeted as focus areas for the subsequent prescriptive study in the research.

This part of the study was done by arranging three workshops that served the purpose of formulating – on the basis of the PFMP - a recommendation for further actions. This recommendation was to be presented before a product committee composed by the CEO, CMO, CFO, CTO and COO of Danfoss AC.

The agenda for the workshop was basically to present the PFMP and then force the attendees identify and prioritise improvement potentials in the product family based on the information brought forward by the PFMP. The initial intention was to interfere as little as possible, but to clarify questions about the technicalities in the PFMP tool if necessary, and observe the attendees. Dependent on the outcome I/we would facilitate the session further and if necessary participate in the work as a Danfoss AC employee in addition to the role as researcher.

Since the relations between the products and other product life phases is a object for this research the workshop was arranged to be cross-functional in order to facilitate discussion of such relations. One or more different employees from the engineering department, the R & D department and product management attended all of the three workshops together with a production technician and/or a production planner from one of three value streams in the factory. Additionally, employees from the purchasing department attended two of the three workshops. Hence, the workshops had approximately ten Danfoss AC employees as participants.

Normally, the results of a descriptive study can be captured in a so-called *reference model*, which describes the how success criteria through the measurable criteria link to the network of influencing factors. The reference model along with additional experiences and conclusions from the descriptive study (I) is presented in part 4, 'Requirements'.

2.5.3. Prescriptive study

Basically the prescriptive study is focused on developing support, which can have a positive impact on the success criteria by addressing one or more of the influencing factors identified in the descriptive study (I).

The development of methods remains a creative activity in which experience and assumptions will inevitable play a role. The descriptive study (I) and reference model serves as a beacon for the development of the supporting method. In this context previous use of the PFMP tool in research and consultancy within the research group provide a source of invaluable experience.

The setup of the prescriptive study was split in two tracks;

- The Danfoss AC case study
- Product platform course at the Technical University of Denmark, DTU

These will be described in the following sections and the resulting tool developed in the prescriptive study is described in detail in section '2.5.3. Prescriptive study'.

The Danfoss AC case study

The pre-project (descriptive study I) led to the recommendation that Danfoss AC should initiate a development project to address the growing complexity by re-designing the entire solenoid valve product family based on product platform and modularisation concepts.

Consequently, Danfoss AC brought together a project team consisting primarily of full time product developing resources but with part time production technicians and marketing resources allocated to the project as well. Figure 2.6. illustrates the organisation of the project team.

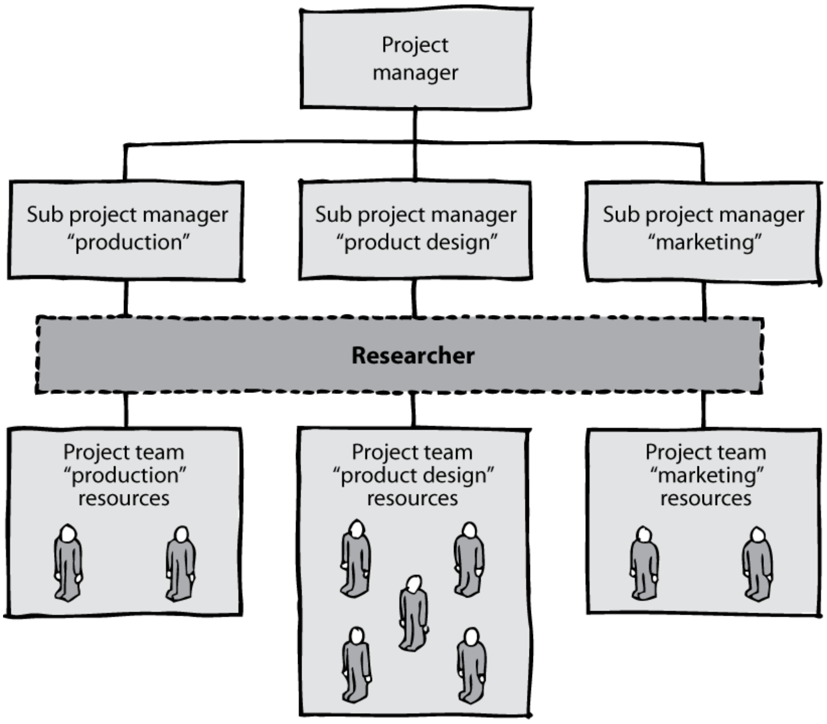

Figure 2.6. *Organisation of the project team in the Danfoss AC case study. The project is organised in three separate tracks focusing on product design, production setup and marketing relates issues respectively in accordance to integrated product development [Andreasen & Hein, 1987].*

In compliance with the mindset described in *integrated product development* [Andreasen & Hein, 1987] the project team is divided in three separate streams (including dedicated sub project managers) to ensure that relevant issues about product, production and market are addressed. The project manager's primary responsibility is to align the work in the three tracks ensuring a common aim for the project.

The organisation of the project is relevant since modelling of relations between the products and other life phase system in the form of production and marketing is one of the primary objectives for this research, and having a separation of the project team in three streams suits conveniently into this.

In this part of the research I (together with another researcher associated to the project) took a role as a more participating member of the project team in Danfoss AC. My role was to support the product manager and sub project managers by extracting relevant information from the three tracks and implement this in the support tool, which is the subject for the research. This action research approach meant that the development of the support tool in practise consisted of many small iterative loops of prescriptive and descriptive actions – i.e. I would present a preliminary version of the model to the project team and the advantages, drawbacks and general relevance of the model was discussed and evaluated. Experiences from these iterations would serve as input to the next generation of the tool, which would go through a similar process.

Product platform course at the Technical University of Denmark, DTU

Apart from the actual case study at Danfoss AC I had the opportunity to get input from students at the university to the development of the tool.

In a new course, "Technology platforms and architectures", the students in groups of two were to analyse a product family using the PFMP tool and on this basis recommend a new product design based on product platforms and architectures. The intension of the course was to use real case from industry in order to make the process more realistic.

Fortunately, Danfoss AC allowed us to use the solenoid valve business as bearing case in the course, meaning that 105 students in two semesters (57+48) analysed the solenoid valve product family and thereby could give input to this research.

In the analysis part of the assignment the students were instructed to deliver 3 posters (fig. 2.7.), which should describe the solenoid valve market, product family and production/supply chain respectively, plus a small report describing potential focus areas for re-design.

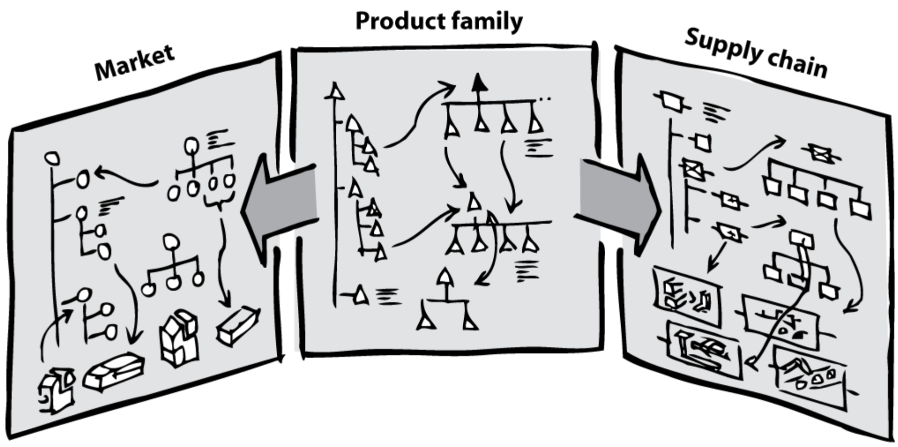

Figure 2.7. *The students in the product platform course at the Technical University of Denmark, DTU was instructed to include market, product and production/supply chain aspects in their analysis of the Danfoss AC solenoid valve product family, and to present their analysis visually on three posters.*

The students were instructed to comply with the requirements to the tool, which was identified in descriptive study (I) (part 4, 'Requirements'). Furthermore, they were urged to focus on the relations between the products and the production.

For practical reasons the students had only limited data available and had no direct access to market, product or production experts at Danfoss AC. The role as expert was filled inadequately by me and another researcher with experience from Danfoss AC. In cases where students had need for information that was unavailable, they were provided with fabricated data enabling them to implement their ideas.

The result of the two courses was 50 suggestions to how the PFMP tool could be enhanced to meet the requirements identified in this research (fig. 2.8.). The work was presented to the project manager and sub project managers in the Danfoss AC project team to evaluate the students' ideas.

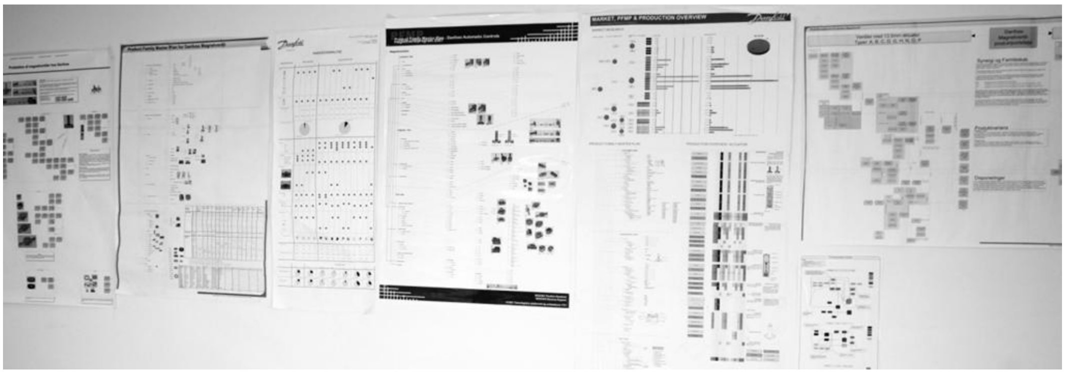

Figure 2.8. *Examples from the "Technology platforms and architectures" course of students' suggestions to how the requirements could be met by visual models. Their work provided a tremendous amount of input to the development of the prescribed support.*

This part of the prescriptive work has provided a tremendous amount of input to the development of the tool.

2.5.4. Descriptive study II

The aim of the descriptive study (II) is to make a formal evaluation of the results of the prescriptive study. Moreover, one can expect to get valuable experience from an implementation of the research results which can serve as input to changes and improvements of the results.

The results of this study and research has been implemented in the case company and used by industrial practitioners. In the beginning it was used as an analysis and later on became the foundation for a more long term product development project. Thus, the research has served as a foundation for decision making with relatively high impact on the business in the company. The experience from this practical application of the research and the way the case study evolved has had a significant impact on the validation of the results, and serves as the basis of the descriptive study II.

A PhD study like the one presented in this thesis, lasts for three years. Large scale product development projects in a company that fits the scope of figure 2.1. are very likely to have a duration of more than three years and are likely to be affected by several aspects other than the research itself. This implies some constraints on the ability to validate the research and conclude on its effects. Due to these time constraints and in order to fully understand the process and the results, the research is validated using a single case – the Danfoss case. This imposes higher demands for the structural logic of the work.

It is not directly possible to measure the overall purpose of this research (See Part 4), i.e. "effective and efficient production of product variety". Even a qualitative impression is hard to obtain. Instead, another way to validate the results against the overall criterion would be an evaluation of the foundation upon which decisions about the product family can be made. The assumption is that management decisions will help the company obtain a more efficient and effective production of product variety if they can base their decisions on a better foundation. Thus, the research is evaluated as such – as a foundation for decision making, even though the overall aim of the project is different. It corresponds to a difference in measurable criteria and research aim, as they are not necessarily the same.

To support the findings of the case study, I have lead a review process including more than 100 design engineers in three different companies and a total of nine different and independent departments have seen the research results and had the change to comment on it and the different aspects related to the decision foundation capabilities. I have also lead extensive discussions with academic colleagues by attending conferences and workshops. Moreover, a total of 105 postgraduate students have worked reviewing the tool as part of a case study in their education.

The most important reviewers of the tools have been a total of persons all of which have extensive experience in the fields of product development and production respectively, some of which were also working on complexity management and product platform development.

The details of how the academic and industrial reviews were performed are described in the following.

Academic reviewers

I have participated in conferences and workshops throughout the study. The three main communities and forums have been;

- The European engineering design community, mainly by attending the ICED conference (International Conference on Engineering Design) in 2005 and the Design Conference in 2006, both hosted by the Design Society.
- The DTM community at the American Society of Mechanical Engineering, by attending the International Conference on Design Theory and Methodology, DTM in 2004.
- The community around the PDMA research forum for the Product Development and Management Association Conferences (The PDMA Conference in October 2005).

At two of the conferences I had the chance to get part of my work presented (ICED and PDMA). The topics of the related discussions at the sessions and after, was focused on the challenges related to modelling of several domains (such as the market, product and production domains) and how to manage the links between these. The idea of different life phase systems in the same product model has also been part of these initial discussions. After the two conferences the work was published in the International Journal of Mass Customization [Mortensen et. al., 2007].

Another source of inspiration has been the alumni network from the Summer School on Engineering Design Research, at which PhD students from all over Europe met to learn more on research methodology within the field of engineering design. (I attended the school in 2005).

Moreover, the research has been refined through two courses taught at The Technical University of Denmark with a total 105 participating students. They were all encouraged to comment upon the research.

All in all I guess that a total of roughly 400 persons from academia have been confronted with the research. Some of these have taken active part in discussions and evaluations of the tool (around 30 of these 400 persons) while the rest has been attending conference sessions or the like. Clearly one does not obtain valuable input from every single participant in a conference session, and if these attendees are not included, I guess that a total of 60 academic persons have taken an active part in the evaluation of the research.

Industrial reviewers

In order to get a less theoretical and more application oriented evaluation, I have had the change to interview quite a few industrial practitioners. Through my work as a consultant and as a PhD student, I have talked to hundreds of engineering design practitioners, but also marketing assistants, purchasers, production workers and other employees of various backgrounds. The most detailed interviews have been conducted with the help from 29 industrial practitioners in five different companies. Two of the companies are consultancy companies working on change management, lean production and lean development. Three of the companies are manufacturing firms – one of them Danfoss. Danfoss is the major source of validation as they have provided 21 of the 29 persons involved in this verification and validation. The 21 persons from Danfoss are from five different business areas, which are run like separate companies within the company, thus having different business cultures and products yet the overall brand and primary markets and customers are the same.

Persons with different backgrounds have been chosen in order to review the research. Some of them are chosen because they where affiliated with the case project while others have been chosen due to their experience or position in the company. The mix of reviewers is as follows; 5 presidents (CEO, CFO, COO, CDO, and CPO), 2 management consultants, 3 managers of operations (i.e. production), 3 managers in product development and 16 design engineers.

In order to keep focus in the dialogue with the industrial practitioners, seven questions where always asked during the relatively informal discussions on the research:

1. *Do you approve of the relevance of the elements in the model? (Theoretical structural validity)*
   The reviewers where asked to express their opinion on relevance of the different parts of the model – from a viewpoint of his/her background and working area and as a whole.
2. *Do you regard your products as representative for your company and the business you operate in? What are the general patterns in your industry when it comes to complex product ranges and the way your competitors go about it? (Empirical structural validity)*
   This question was asked to the Danfoss employees directly involved in the case study or with a relation to the products in the case study.
3. *What are the main benefits – if any – of this research result in your opinion and in this particular case (Empirical and partly theoretical performance validity as well as verification by acceptance?*
   The reviewers where asked to explain the use of the research result in their own department if applicable and subsequently to infer about the general use of the result in other departments and by other colleagues – in and outside of their company.
4. *What are the limitations on the usefulness of this research in relation to the potential areas of application (A limitation of the empirical versus theoretical performance validity).*
   The reviewers where asked to comment on the possible use of the research in different situations based on a starting point in their own daily working life and subsequently infer about the usefulness in a more general perspective.
5. *Are there any aspects of this model that is new to you? (Novelty).*
6. *What possible elaborations and developments of this research do you envision?*
7. *In your opinion, how could this research affect the support for decision making in your company?(Validating the main research objective)*

The meetings were held as relatively informal meetings, and on purpose not setup as an interview, rather an exchange of experiences. The reason for doing it this way was to create a more trustworthy atmosphere and to get formal as well as informal input from the reviewers. A readymade questionnaire would have restrained the reviewers from taking an active part in the dialogue, and some questions might never have surfaced, as a very formal and distant atmosphere does not promote an active involvement of the reviewers.

Four of the 29 interviews were conducted as a single meeting lasting around two hours. The conclusions from the rest of the reviewers are more based on a longer participation and collaboration. The result is more than 130 statements, quotes, and suggestions.

Part 3

Frame of reference

The objective of part 3 is to present the theoretical basis upon which the research work is founded. Part 3 will go through a series of different research fields and disciplines, and describe why they are relevant to the research work presented in this thesis.

The frame of reference presented here in part 3 has deliberately been separated from a review of state-of-the-art product family assessment tools and methods, which are presented in part 5. That is, part 5 presents a review of methods and tools that directly address the requirements established in part 4, whereas part 3 include a review of a broader and more fundamental body of knowledge. Nevertheless, some overlaps between part 3 and 5 do occur.

3.1. Introduction

The framing of the research gives way for a body of knowledge upon which the research is founded. This section will go through a series of different research fields and disciplines, all of which are fundamentals of this research. It is, however, important to note that the contributions of this research lies within an engineering design and product development context.

The frame of reference for this research work is divided in three sections;

- *Engineering design*
  This section presents theories and models – especially product models - within the engineering design, product development and design science community.
- *Multi-product development*
  This section presents the conceptual framework used in relation to multi-product development, i.e. mass customization, platform-based product development, modularization, etc. Especially, the concepts of variety and commonality are discussed.
- *Lean philosophy*
  This section presents the conceptual framework that lies behind the lean manufacturing philosophy. Especially, the concepts of waste and value are discussed.

3.2. Engineering design

3.2.1. Theory of technical systems

Theory of technical systems (TTS) was introduced to *design science* to support the engineering design process [Hubka, 1973], [Hubka & Eder, 1987 & 1988]. A technical system (TS) is the artefact (the product) that together with the human (Hu) and the environment (En) conducts the necessary effects to carry out the transformation or technical process (TP). The technical process is a simple input/output model which describes the change of the input operand(s) state (material, energy or data) to a more desired state (fig. 3.1.).

It is noteworthy that the technical system in itself cannot perform the technical process. Yet, only the technical system can be designed in an engineering design process. Consequently, the technical process cannot be designed directly but is dependent upon the context in which the technical system operates, and the desired process will only take place when the right interplay between operators (TS, En, Hu) occurs.

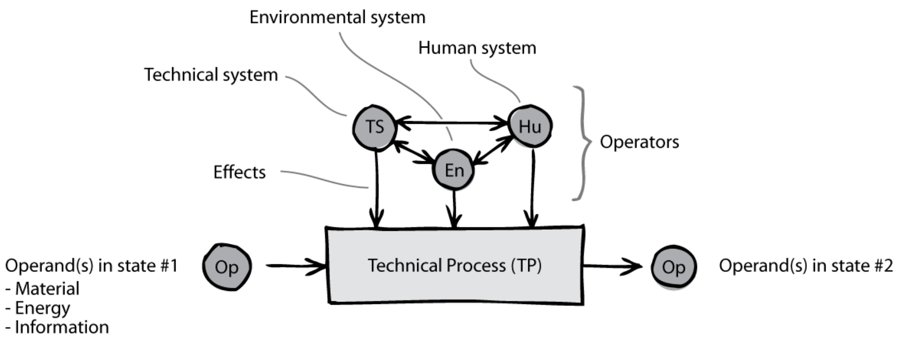

Figure 3.1. *The technical process (TP) is a simple input/output model that describes the transformation of input operands' state (material, energy, data) to a different output state. The technical process is dependent on the interplay between the operators: the technical system (TS), the human system (Hu) and the environmental system (En).*

The relation between TTS and this research

TTS is useful as the underlying abstraction when modelling an artefact i.e. a physical product and the interactions with the surroundings of that product. Since a focal point in this research is the modelling of products, TSS becomes relevant. The most applicable abstraction of the theory is that the product in itself has no effect, yet it happens only in an interaction with the surrounding elements. Many models in literature describe the product from a geometric and/or parts perspective only, and leave it to the spectator to interpret how the parts and subassemblies constitute a meaningful totality through interplay with the inputs and output to and from the surroundings. One of the most common representations of mechanical products is the technical machine drawing. It is a strictly geometrical representation and has no direct information on behaviour or effects. It often takes a product expert such as a skilled engineer or a product manager to interpret a set of machine drawings into an expected set of effects and functions. The drawing itself does not represent behaviour or effects.

One of the prime objectives of this research is to explore and strengthen the present knowledge on modelling techniques for families of tangible (mostly mechanical) products in order to support decision making. Decision making on a product family level is often a hard task mainly due to the complex constraints between geometrical changes in the product and the effects in different life phases of the products.

TTS not only applies to the products in a product family. TTS may also be used to describe the production system upon which the products are made. A production system is also a technical system with the operands being the parts and subassemblies of a product as they pass through the value stream and are changed from one state to the other.

TTS is a useful way of perceiving a product or a production system but it has a focus on the technical process itself. Aspects other than the process are also important when making decisions on product families. Aspects like the physical structure of the product, the assembly sequence, the effects arising from the interaction in different life phases

or different perceptions of a product in different professions are not directly incorporated in TTS. The following theories and models are more or less elaborations of TTS. They describe different aspects closely related to decision making on product families.

3.2.2. Theory of domains

The theory of domains (ToD) was introduced by Andreasen [1980]. The theory of domains states that the design of complex machine systems consists of the describing of 4 systems; the process, function, organ and part system referring to 4 domains (fig. 3.2.).

Within each domain systems can be described at different levels of abstraction and different levels of complexity. The design process is by nature not as simple as illustrated in figure 3.2., and will normally include loops back and forth between the domains, starting the design process making an abstract and general model and continuously specifying more concrete and detailed models of the systems, to finally end up with a completely specified system (a product).

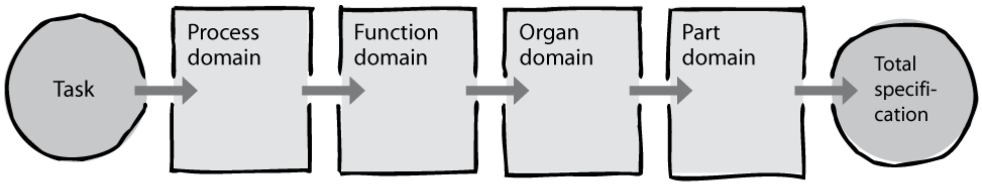

Figure 3.2. *Sequential specification of the process, function, organ, and part system in the design process is the basic concept in the theory of domains [Andreasen, 1980].*

Process domain

The modelling elements in the process domain are operations, which can be understood as technical processes transforming material, energy and data to a new state as described in the TTS [Hubka, 1973], [Hubka & Eder, 1988]. The sequence of the operation elements describes the structure of the model, and the relation between the elements is described by the input/output state of the operands (material, energy and data).

Function domain

The term process is used to describe the overall purpose of the system (product), while the term function is used to describe the product's capability. The product poses the ability to create the necessary effect because it poses a certain function.

Hence, the function domain takes includes power, control, assembly, and support functions into the model. The modelling elements in the function domain are accordingly functions. The grouping of functions and the designation of effectors and receptors make up the structure of the model.

Organ domain

The organ concept is used to describe the functional element, which are the entities that create the product's functions described in the function domain. Thus, organs are also known as functional carriers. An organ consists of so-called material areas which by their properties and arrangement creates a certain effects (functions).

Organs do not normally correspond to component or sub-assemblies. Organs material areas can be distributed among several components, and one component can have several material areas, that are part of different organs.

Organs enable the explanation of functions, which is not possible when modelling components and sub-assemblies [Mortensen, 2000].

Part domain

The part domain describes the physical realisation of the organs. The parts are described in terms of form, material, dimension, tolerance, and surface as well as the interrelation between the parts in order to compose the necessary organs. An assembly drawing is one example of modelling the part structure of a product

The relation between ToD and this research

The theory of domains provides a strong elaboration of the TTS. The strength of ToD lies in the ability to work with several levels of abstraction of the same product. It is useful in a change process and in relation to decision making. The part domain is the most tangible of the four domains, and it is often on a parts level, companies start searching for improvement potentials. The problem is that the largest potential is not always found in parts and subassemblies. ToD provides new viewpoints in the search for improvement potentials, and is thus useful as a theoretical foundation for a model with such a purpose.

The ongoing redesign and optimisation of a mature product range is often done through incremental development of parts and subassemblies. The overall layout of older mature products is seldom changed. This is partly due to conservatism and partly, as described in the introduction, because the complexity dilutes a total overview and prevents the necessary decision making from taking place. With a traditional parts focused approach, a company will not be able to fully get rid of the problems related to complexity. It takes an overall change process including organs and functions, to really exploit the full potential of a product family rationalisation.

The organ domain is perhaps the strongest of the four viewpoints. Complexity often occurs when specific functions are embodied in different ways across a product family. When several products are different from a structural viewpoint, but still carry the same functions from a customer viewpoint, the products are unnecessarily complex. The organs, the function carriers, are different even though the functions are the same. In order to change that, the design engineers have to understand that there such a thing as organs and the role they play in a redesign process.

3.2.3. Multiple structures

Design engineers normally use machine drawings or sketches to describe the product structure. As discussed earlier a drawing is mainly a geometric representation of the product with little or no information on functions, effects and other aspects of the product.

But a product is much more than its physical components. Different functional areas in a company may find the physical product structure insufficient. The financial department will have the need to describe the product in economic terms and form a product structure based on costs – instead of parts and subassemblies. Other departments will have other needs.

According to Andreasen et al. [1995] *the structure of a product is the way in which its elements are interrelated in a system, based on the actual viewpoint*. Consequently, a product has multiple structures depending on the viewpoint. Four basic views seem to exist (fig. 3.3.):

- *Synthesis oriented or generic product structure*
  The product structure can be modelled according to the four domains in the theory of domains: process, function, organ and part domain [Andreasen, 1980].
- *Functional views on structure*
  A product can be modelled according to the different disciplines describing the product, (e.g. electronics, thermodynamics, control, etc.), using the coherent domain language to define the product structure.
- *Product assortment view*
  When products are modelled from an assortment point of view the similarities and differences, i.e. commonality and variety, between the products is the focal point for the product structure.
- *Product life views on structure*
  The product life views relate to the products meeting with different product life phase systems, e.g. production system, transportation system, service system etc.

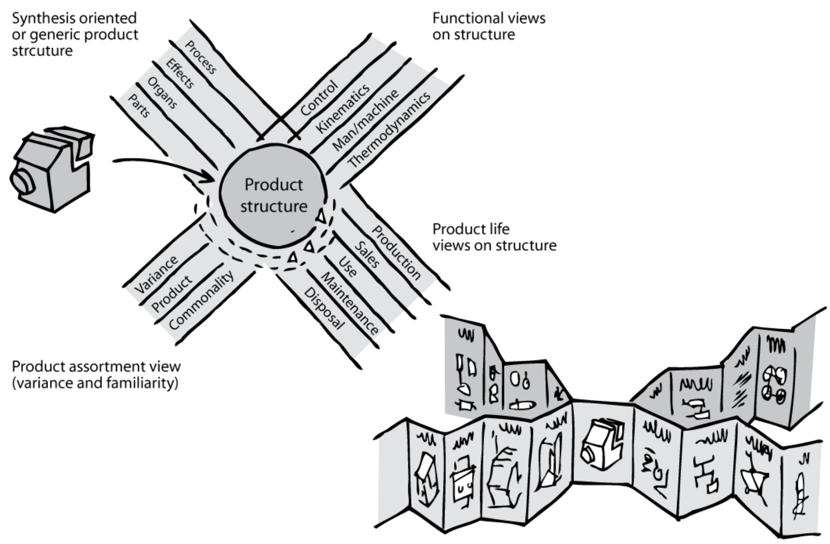

Figure 3.3. *The four basic classes of structures of a product. A product's structures are multiple and depend on the viewpoint taken [Andreasen et al., 1996].*

The relation between multiple structures and this research

The aspects described by the theory of domains are not the only viewpoints needed when optimising and redesigning products. The idea of multiple structures and the idea that they depend on viewpoints is useful in order to keep track on the consequences of a design change process. It is also relevant when analysing a product assortment, because the different viewpoints will address different aspects of the performance of the product assortment and help identify improvement potentials. In that respect it fits very well with the research aim of this thesis.

3.2.4. Theory of dispositions

According to Olesen [1992] a disposition is understood as *that part of a decision taken within one functional are which affects the type, content, efficiency or progress of activities within other functional areas*. That is decisions about the product design facilitate or impede what solutions can be chosen in the design of the life cycle systems. These decisions are made long before the actual production, transport, use or disposal of the product – hence the term *disposition*.

The fit between the product design and the life cycle systems determines the overall performance of the product throughout the entire life cycle. The product design and the life phase system should be fitted to each other and/or designed concurrently to achieve the optimum performance (fig. 3.4. and 3.5.).

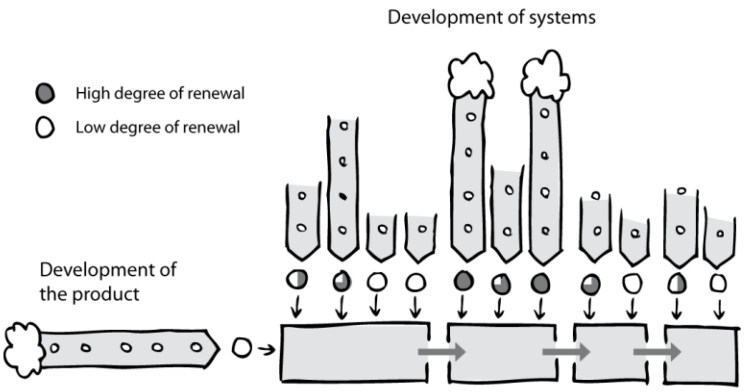

Figure 3.4. *A product life cycle model. Some of the life cycle systems are renewed while others are re-used completely or to some extend [Olesen, 1992].*

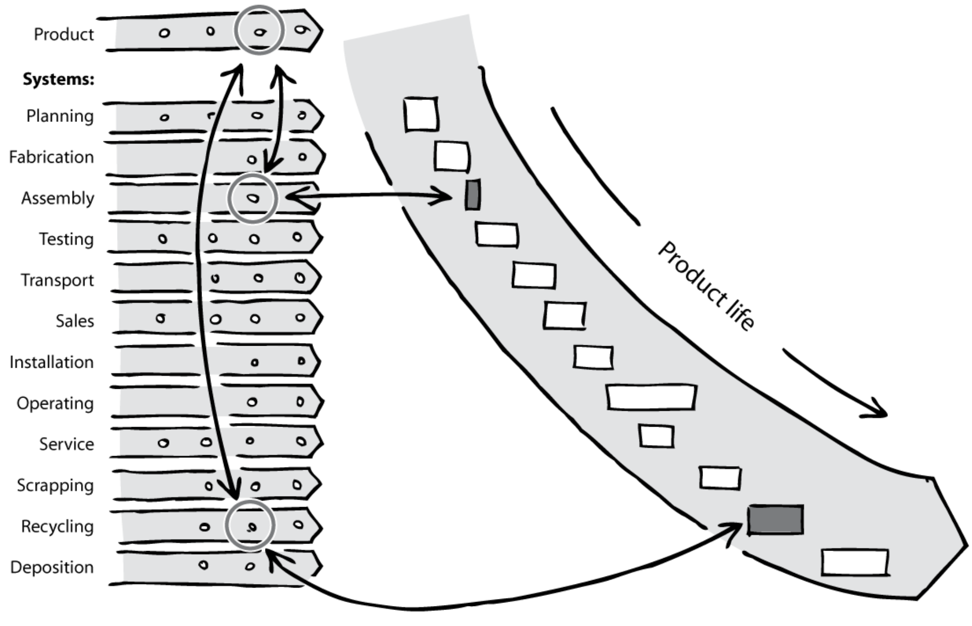

Figure 3.5. *A product passes through a series of different life phases and will enter several so-called meetings in those life phases. The effects arising in those meetings is a function of product design and the characteristics of the particular life phase in question [Olesen, 1992].*

A central part of the theory of dispositions is the idea of *meetings*. The product goes through several meetings in the different life phases. Each of these meetings corresponds to relational effect – an effect arising from the meeting between the product and “something else”. The OEE (overall equipment efficiency) is an example of a result of such a meeting. The efficiency of a production line is a consequence of the product design *and* the production system.

When the Danish brewery, Carlsberg introduced a new, modern design of their bottles in 2004, they underestimated the consequences disposed by the new design. The new bottle was more slender than the old design and did as a result not fit into the same crates. Thus, the new bottle design resulted in a new crate design. Again, this new crate did not fit into the counters in the bars, since these counters has been standardised to serve the old crate design. Nor could it be stacked together with the old crates, which was still the standard used by every other major Danish brewery at the time. In the end the pressure from the bars and restaurants forced Carlsberg to discontinue the new bottle and crate design and re-launch the original bottle and crate [Ritzau, 2004 & 2005].

The relation between the theory of dispositions and this research

The theory of dispositions is relevant to this research because the mapping of dispositions – especially regarding the production system and the supply chain in general – should play a significant role when concluding on a product assortment’s ability to support efficient manufacturing of the different product variants.

3.2.5. Genetic design model system

The Genetic design model system (GDMS) [Mortensen, 2000] takes in elements from the theory of technical systems, the theory of domains and shares the life phase aspect with the theory of dispositions as it takes into consideration the notion of meetings. GDMS has elaborated the idea of the *chromosome model* [Ferreirinha et al., 1990]. The chromosome model is a representation of the domain theory in which causal relations are mapped. The chromosome model in its original form is omitted in figure 3.6., as the GDMS is sufficient.

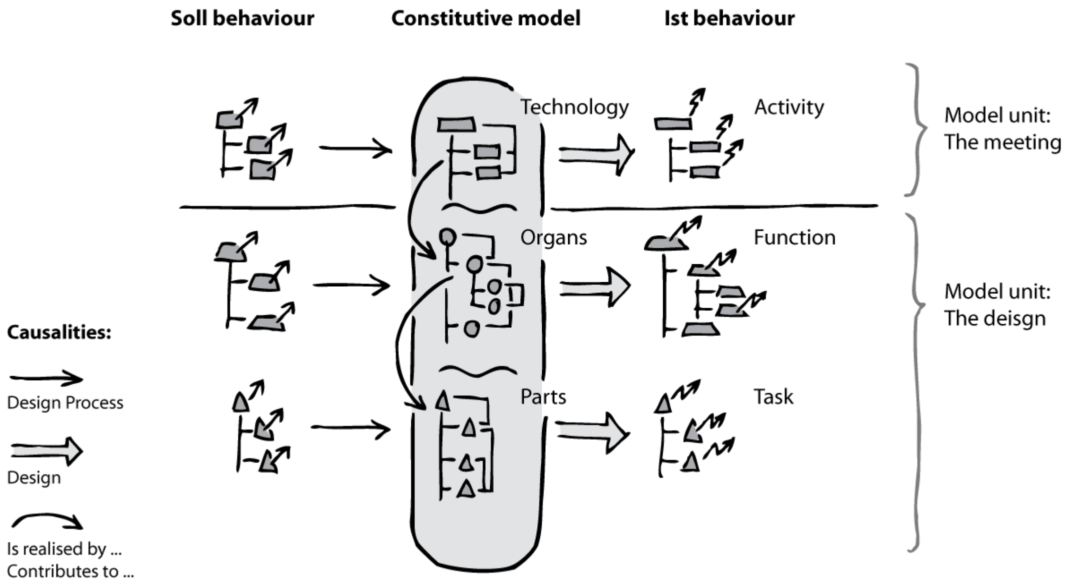

Figure 3.6. *Constitutive and behavioural aspects of the chromosome model [Mortensen, 2000].*

Attributes, characteristics and properties

Attributes describing and defining a design are called *characteristics* (and defines the physical building principles of the product) whereas attributes describing and defining the behaviour of a design are called *properties* (defines the way the product works). Properties can be inherent or relational.

- *Inherent properties*
  Inherent properties are those properties that are intrinsic in the product and possessed by the design itself. Tjalve [1976 & 2003] provides a set of inherent properties; form, material, dimensions and surface quality. From the basis of these properties one is able to fully define a product from a design point of view.
- *Relational properties*
  Relational properties are those properties that describe the meeting between the product and one of the life phases.

The GDMS elements

The modelling scheme in GDMS has a clear distinction between the meeting and the design as well as the behavioural and constitutional attributes of the product.

- *Constitutive model – what is the product?*
  The constitutive model defines the inherent properties of the product in the design domain and the technologies of the product in the meeting domain.
- *Behavioural models –what does it do?*
  The behavioural model defines the characteristics of the product. The behavioural model is split in a Soll behaviour and Ist behaviour. Soll/Ist is German for should/Is. In other words these two parts of the behavioural model describes the difference in the intended design before the design process and the actual design after the design process.

In GDMS models describing the meeting and models describing the design itself are different. The top level of figure 3.6. describes the meeting. It corresponds to the process domain of the domain theory. The technologies in the product may be seen as the carriers of effects in the process domain of the domain theory. The technologies are realised by organs that are realised by parts. Note that the function domain has been removed from the constitutive chromosome model because functions are not constitutive but has to do with behaviour.

The relation between GDMS and this research

The strength of the GDMS is the clear distinction between behavioural and constitutional models as well as the meeting/design split. One of the research challenges of this thesis is to support a diagnosing process within a company in which a search for improvement areas proceeds. When analysing a product assortment for improvement potentials it is very important to state whether a particular finding is directly related to the product design, a behavioural characteristic or an effect arising from a meeting in one of the life phases. If, for example, an analysis points out that there are problems with cost and efficiency in the production, it is noteworthy that the analysis should also point out to what extend it is a symptom of the design, the production system, the actual meeting between these two or a combination of them. This has to do with the state of alignment as described in the introduction. The term *alignment* refers to the process in which a company through a purposeful process is trying to create a fit between the product and one or more life phases – mainly the production. The analysis challenge of the thesis work has to support the alignment process on the way from a complex product assortment into a more streamlined assortment with less complexity related costs.

3.2.6. Design theory

The design process has been described by several authors. Some are more theoretical descriptions of the nature of design while others are more laid out as prescriptive models describing the steps of a design process [Pahl & Beitz, 1977 & 1996], [Hansen ,1974], [Hubka, 1976], [Copper, 1993], [Ulrich & Eppinger, 2000].

The theory of technical systems and the chromosome models from GDMS, is used in this thesis as the underlying framework for understanding what a design (within the paradigm of technical systems) is. The domain theory states that the design process is a gradual concretisation of the process domain, the function domain, the organ domain and the part domain respectively. In practice this process will be iterative, while the concepts and designs get more concrete.

The engineering design process itself – the actual design of the physical artefact in focus – is described by Tjalve [1976], as a detailed process in which alternative means and functions are concretised successively (fig. 3.7.).

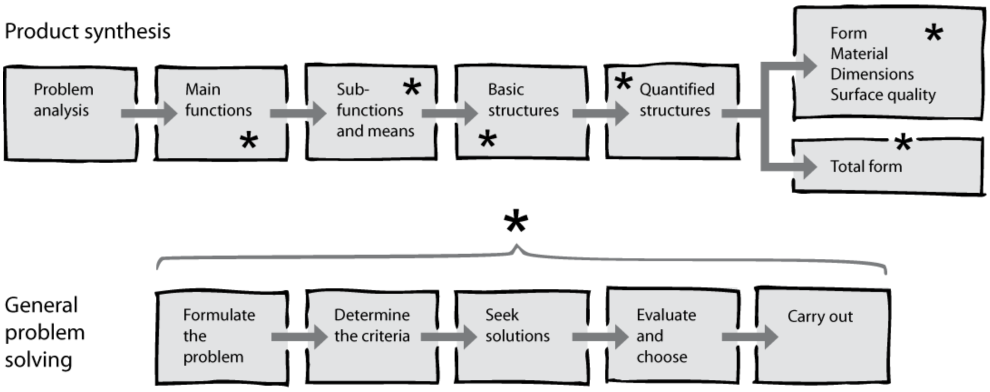

Figure 3.7. *The engineering design process formulated by Tjavle [1976]. The design process gradually becomes more detailed. Although drawn as a linear process, the engineering design task is highly iterative. The stars denote that a general problem solving approach is applied in each task in the process.*

This engineering design process was put into a product development framework by Andreasen & Hein [1987]. Their work is very important to this work, as the idea of a concurrent approach is very fundamental to the research work in described in this thesis. The book contains a model for concurrent development of market aspects, product design and production system (fig. 3.8.). The benefits of a concurrent approach is obviously the possibility to align the products with the production system (and vice versa) and obtain a fit to the market using a structured process to meet customer demands, as opposed to a more ad hoc approach in which the products are developed and then "thrown over the wall" to the production department, and finally pushed to the market place hoping that someone will buy them.

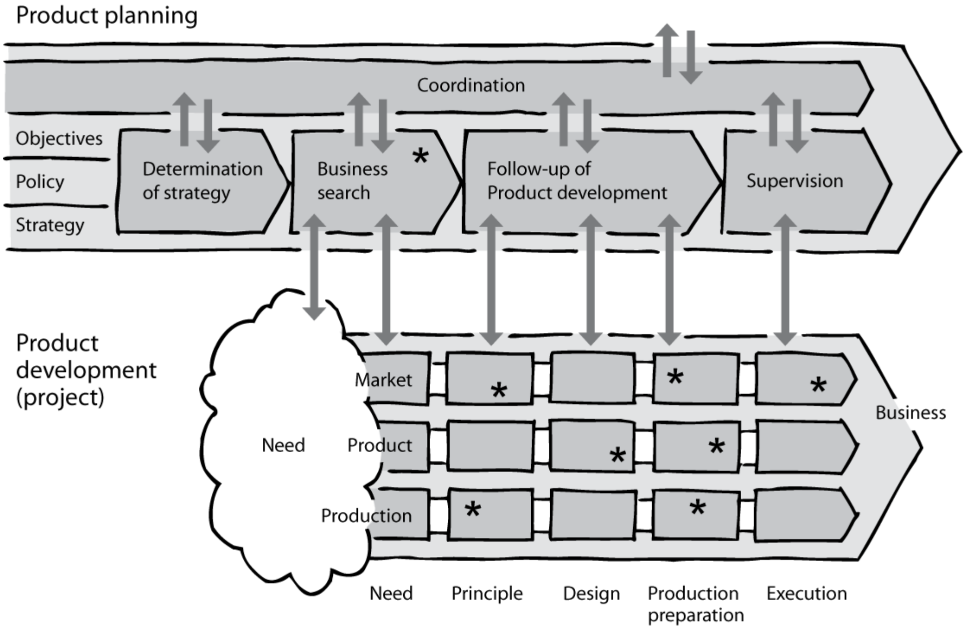

Figure 3.8. *The Integrated Product Development model. Product planning is coordinated with combined task of bringing a product to the market place using an integrated approach in the market, product and production domain [Andreasen & Hein, 1987].*

The relation between design theory and this research

A product assortment is a result of a series of design processes. Most mature product assortments have been expanded throughout many years through the use of different design steps. New product variants are added, and existing product variants are modified in order to meet changing customer needs. In order to understand the products (as a result of the design process) it is also important to understand the design process itself. One of the objectives of this research is to formulate an analysis framework for product assortments, and it therefore seems natural to include into the model, aspects that are important to the subsequent product development activities. It then also seems natural to understand the nature of design processes, while studying the need for such an analysis framework. Moreover, the integrated product development scheme in itself is relevant, as the idea of a concurrent analysis of market, product assortment, and production aspects originated in that work.

3.3. Multi-product development

The term multi-product development is used to denote different paradigms related to more efficient and effective development and production of product variety, i.e. mass customization, platform product development, modularisation, etc.

The topics are not within the core of this research work, but the conceptual framework behind the different multi-product development paradigms are closely related to the challenges connected to managing growing complexity in mature product families.

The following sections cover the most important aspects of the conceptual framework behind the multi-product development paradigms.

3.3.1. Variety and commonality

As described in Part 1 it is a core challenge for companies to offer products with great variety of products to the marketplace (i.e. customisation) and still make it possible to exploit the benefits of economies of scale in the production/supply chain. Traditionally, product variety has been considered as an equal trade-off (fig. 3.9b), where variety is valuable in the market but is costly to obtain [Berglund & Claesson, 2005]. The thought behind mass customization, platform product development, modularisation, etc. is deriving highly distinct products effectively by minimizing non value-adding variety and creating commonality in the products.

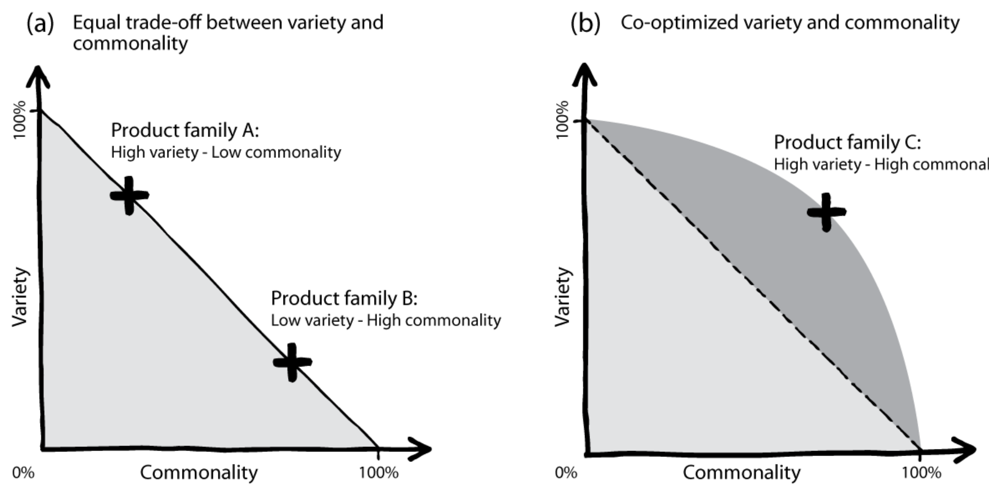

Figure 3.9. *Trade-off between variety and commonality: (a) traditionally variety and commonality has been considered as an equal trade-off, (b) since variety and commonality is measured in different relations they can be co-optimized.*

Commonality is not only about using the same components. If this was the case we could conclude the equal trade-off between variety and commonality (fig. 3.9a). That is not necessarily the case, though, because variety and commonality are relational properties in a product, which are only seen in relation to something else (fig. 3.10.). That is;

- *Variety*
  Variety is a property that is seen in relation to another product and is perceived in the products' meeting with another life phase system [Olesen 1992]. Variety is especially desired in the life phase systems related to sales and marketing, i.e. externally.
- *Commonality*
  Commonality is a property that is seen in relation to another product and is perceived in the products' meeting with another life phase system [Olesen 1992]. Commonality is especially desired in the life phase systems related to the production of the products, i.e. internally.

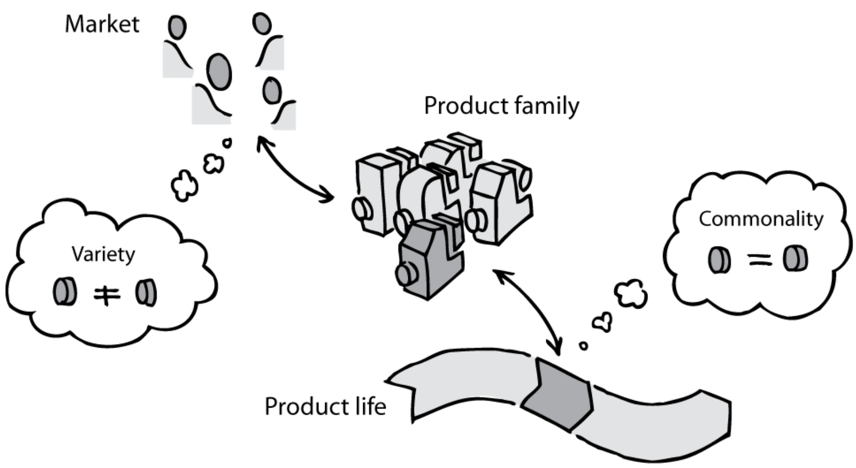

Figure 3.10. *Variety and commonality are relational properties. Products have variety if they are perceived as different from a customer perspective and commonality if they are perceived as alike from a viewpoint in one of the life phases. A well designed product family may have products with variety and commonality at the same time.*

Because variety and commonality are perceived from different viewpoints simultaneously, two objects can be perceived as different (variety) in for instance the market and at the same time be perceived as common (commonality) in the different product life phase systems (e.g. in product assembly).

One example of co-existing variety and commonality is the Swatch wristwatches. The expression (design, colours, patterns, etc.) of different product variants is perceived as product variety in the market, but the assembly line cannot tell the difference and handles the different product variants as they were the same.

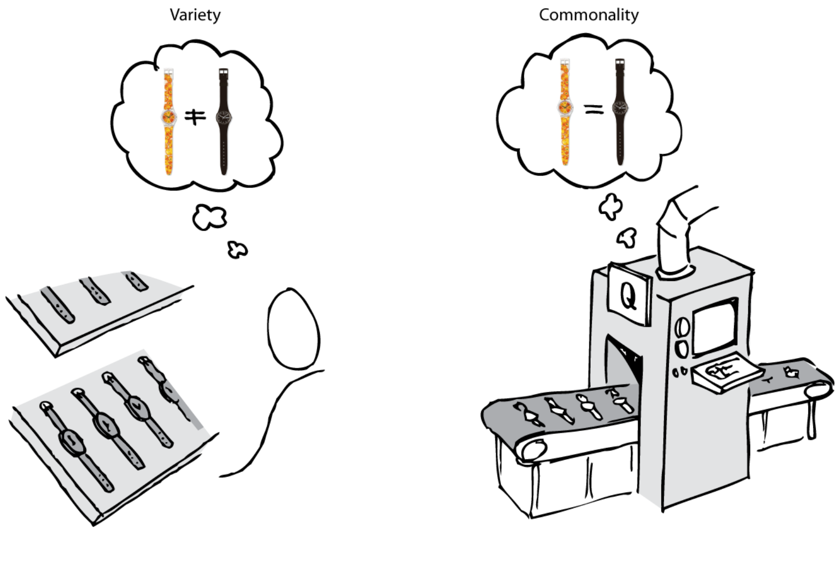

Figure 3.11. *Although the Swatch company offers an endless amount of wrist watches in all kinds of colours and combinations they are not burdened by corresponding complexity in the assembly process, as the product variant share a common assembly structure.*

To summarise we explain variety and commonality as relational properties, and that it is possible to co-optimise them and leverage distinct products more effective and efficiently (fig. b). This is fundamental concept behind mass customization and product platform strategies.

Variety and commonality in relation to this research

The concepts of variety and commonality are relevant to this research, as one possible way to improve the ability to produce product variety more efficiently and effectively are to co-optimise variety and commonality, i.e. achieve to present the desired variety towards the market and simultaneously present a high degree of commonality towards the production system and supply chain.

Consequently, identification of non-utilised potential of co-optimising variety and commonality is a subject in relation to product family assessment.

3.3.2. Mass customization

Mass customization is described as *production of goods and services to meet individual customer's needs with near mass production efficiency* [Tseng & Jiao, 2001]. According to Pine [1993] *mass customization is a synthesis between the two long-competing systems of management: mass production of individually customized goods and services.*

In mass production low costs are primarily achieved through economics of scale, i.e. lower unit costs of a single product through greater output and faster throughput of the production processes. In mass customization low costs are primarily achieved through economics of scope, i.e. the application of a single process to produce a greater variety of products or services cheaper and more quickly [Pine, 1993].

Pine [1993] furthermore describes four types of mass customization:

- *Collaborative customization*
  Firms talk to individual customers to determine the precise product offering that best serves the customer's needs. This information is then used to specify and manufacture a product that suits that specific customer.
- *Adaptive customization*
  Firms produce a standardized product, but this product can be altered (customised) by the end-users themselves.
- *Transparent customization*
  Firms provide individual customers with unique products, without explicitly telling them that the products are customized.
- *Cosmetic customization*
  Firms produce a standardized physical product, but market it to different customers in unique ways.

Implementation of mass customization

Madsen [2001] lists eight means to support successful implementation of a mass customization strategy:

1. *Understand market and customer needs*
   In pursuing the desire to meet any customer demand one could easily motivated to add features that would only add extra costs and complexity. To avoid this it is important to create a clear vision of the actual market and customer demands.
2. *Create a modular product platform*
   A flexible product design is a prerequisite to implement mass customization. Product platforms and modularisation are discussed in the subsequent section.
3. *Postpone creation of variety as close to the customer as possible*
   Postponement is closely related to mass customisation. Postponement is about postponing activities and creation of variety until an actual demand arises. Figure 3.12. illustrates different postponement strategies.

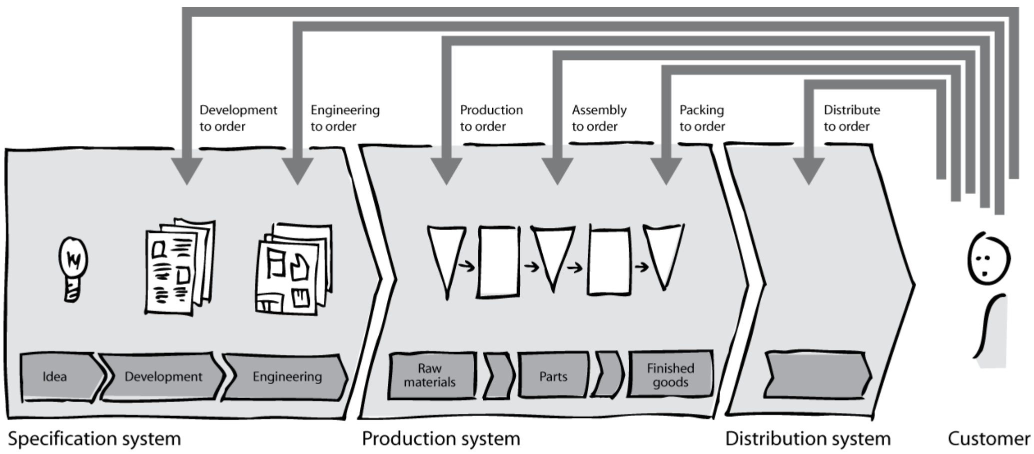

Figure 3.12. *Different postponement strategies: A specific customer order can enter in numerous points in the supply chain, which will correspond to different ways of doing business: develop-to-order, engineer-to-order, production-to-order, assemble-to-order, pack-to-order and distribution-to-order [Madsen, 2001].*

4. *Establish flexible production processes*
   Flexible processes are a prerequisite to obtain economics of scope, which is the means to achieve lower costs.
5. *Create an order- and product configuration system*
   The ability to capture and manage customer orders fast and reliable is a key success parameter to the implementation of mass customization.
6. *Exploit the value of integrated information systems*
   Mass customization requires a lot from the company's information systems. It is important that systems for customer and sales orders are coupled to systems that manage purchasing, production planning, distribution, etc.
7. *Integrate supply sources and distribution channels*
   It requires a lot from the logistic system to support the dynamics and uncertainties related to mass customization. It is crucial that the company control the entire supply chain to near perfection. Figure 3.13. illustrates the conceptual supply chain.

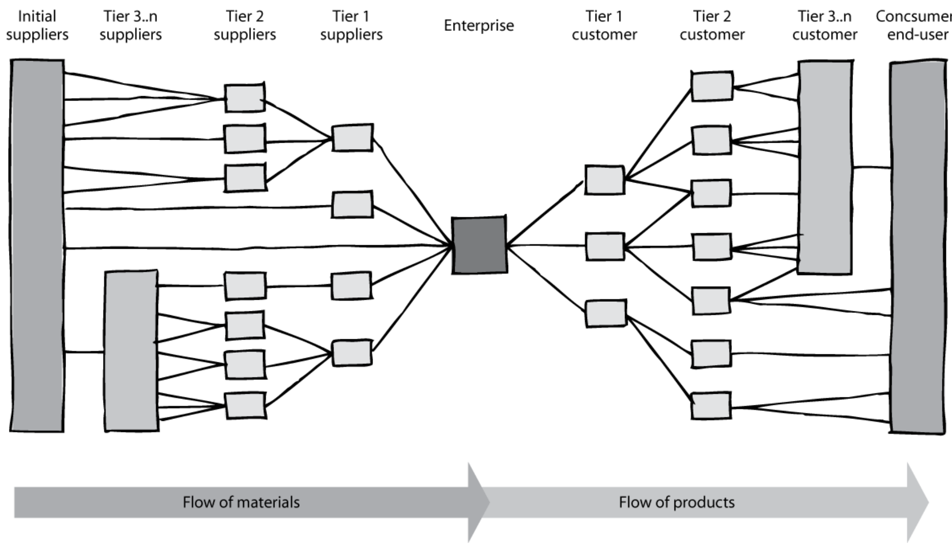

Figure 3.13. *The conceptual view of a supply chain. The box in the centre represents the company of focus(enterprise) [Lambert, 2000].*

8. *Implement Activity Based Costing (ABC)*
   Traditional economic models are design to suit mass production and do not support mass customization and economics of scope. Activity Based Costing is a suitable alternative.

Mass customization in relation to this research

The idea of providing customized products at near mass production costs is of course relevant to this research work.

Interesting is it that the mass customization demands not only attention to improving production efficiency or the like. Implementing a mass customization strategy requires attention to nearly all aspects of a company and the success is dependent on alignment between the different product life phase systems. This way of thinking is highly relevant to this research work.

Especially relevant to this research project are the first four steps described by Madsen [2001] as they particularly address alignment between the products' design, the market demands and the production setup.

3.3.3. Product platform

Product platforms are a useful means to enable reuse of parts, assemblies, technologies, concepts, knowledge, etc. and hereby reduce complexity and improve the business potential [Meyer & Lehnerd, 1997], [Andreasen et al., 2001].

A large academic body of researchers agree that a product platform is the way to achieve both commonality and variety at the same time. The most important difference to the traditional single product development approach is that the development of the individual products is divided in two (fig. 3.14.);

- *Preparation*
  Development of the product platform (i.e. the foundation) from which distinctive product variants then can be derived. The objective of the preparation phase is to secure commonality between the product variants.
- *Execution*
  Development of the individual product variants based on the elements (i.e. components, design rules, etc.) in the product platform.

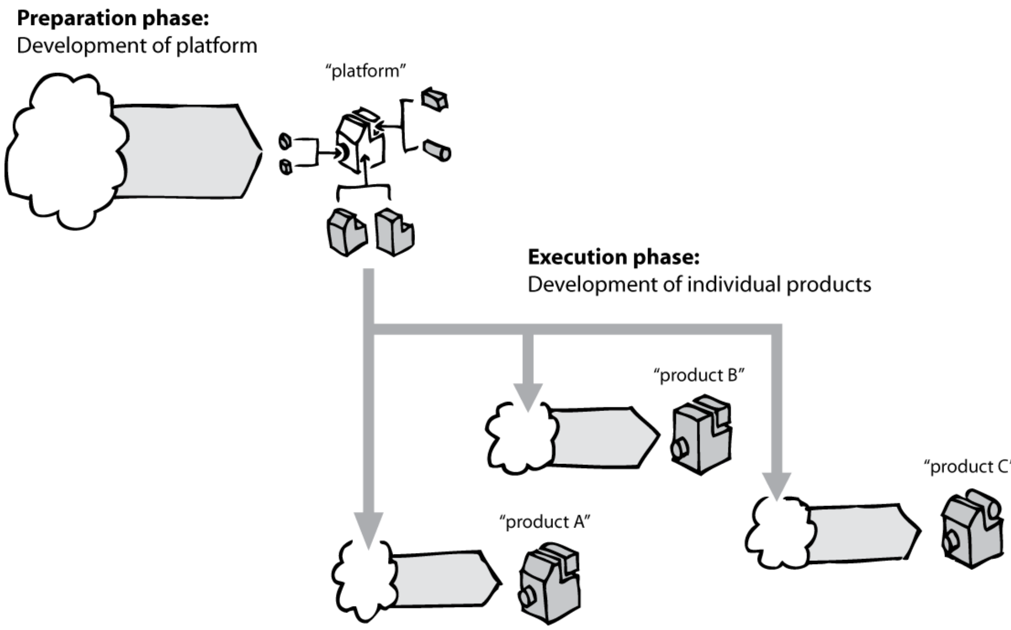

Figure 3.14. *In platform-based product development the development task is divided into a preparation phase (i.e. development of the platform) and an execution phase (i.e. development of the individual product variants) [@].*

Literature describes a whole range of different definitions of platforms. It is not part of this research to provide yet another definition, but it is useful to give a small review of existing definitions and viewpoint on product platforms in order to discuss the notion and to create an understanding suitable for the work in this thesis.

Product platforms are often described as *the collection of assets that are shared by a set of products* [Robertson & Ulrich, 1998], [Ulrich & Eppinger, 2000], [Harlou, 2006]. Other definitions include *a set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched* [Meyer & Lehnerd, 1997]. *Assets* are a rather broad and abstract term while *components, modules and parts* are very tangible. These are typical differences in the perception of the idea of a product platform. Some authors see a platform as a common set of 'building rules' while others are more focused on the actual 'building blocks', the components and subassemblies that are put together to make derived products. The building rules on the other hand are often referred to as the product architecture. Some even define the platform as a *common architecture* [Erens,1996], [Sanchez & Collins, 2001], [Andreasen et al., 2004].

Through this research and a series of consultancy projects it is a clear experience that both types of platforms - as well as intermediate combinations - are found in industry. It seems to make little sense to make one universal definition of a platform, but it does make sense to note a few core elements of all product platforms:

- *Reusable core*
  The product platform defines a reusable core from which a series of product variants may be derived.
- *Intention*
  The product platform is a design preparation and it has an intention of creating a positive "commonality" effect in the products' meeting with one or more life phase systems (e.g. production).

A product platform is often related to the term product architecture and/or a modularised product assortment. These two aspects are discussed in the following sections.

Product architecture

Some authors see the architecture as a characteristic of the product whereas others see the architecture as a structural description of the product. Regardless of the perception of the term product architecture, it is very often used in conjunction with the idea of product families, and the type of product development, in which multiple (rather single) products are developed.

In American literature on product development, the term product architecture is often used to describe how products are decomposed into different subsystems, how these subsystems and their coherent interfaces are arranged in the product [Robertson & Ulrich, 1998], [Stone et al., 2000], [Meyer & Lehnerd, 1997], [Ulrich, 1995]. These subsystems are often described as containing a specific functionality, and the combination of the functionalities of the subsystems creates the overall functionality of the product [Sanchez & Collins, 1999], [Ulrich & Eppinger, 2000]. Using this definition, all products have a product architecture.

Others see the architecture as a *description of the decomposition of a product into modules and the arrangement and interfaces of these modules* [Erens, 1996], [O'Grady, 1999], [Harlou, 2006].

In general – whether we see the architecture as a characteristic of the product or a description of the product, an architecture has to do with the following three things;

- *Decomposition*
  An architecture is a decomposition of a product into sub-systems (modules)
- *Arrangement*
  An architecture describes the relative arrangement of these sub-systems (modules)

- *Interfaces*
  It describes the relations (interfaces) between these sub-systems (modules) and with the surrounding environment

Harlou [2006] expands the idea of an architecture and distinguishes between a product architecture, a family architecture and an assortment architecture as the overall rules that describe the building principles of the product, the product family and the product assortment respectively. A product architecture is then a subset of a family architecture that is again a subset of an assortment architecture.

Modularisation

Some authors then introduce the term modular product architecture and thereby take a step away from the more common denomination of product architecture being merely the structure of the product. The term modular architecture is used when the product architecture is decomposed of a certain kind of subsystems, which have standardised interfaces and contains only one or a few functionalities [Ulrich & Eppinger, 2000], [Sanchez & Collins, 2001].

That is, a modular product architecture has a clear mapping from functional units to physical sub-systems with the following characteristics [Ulrich 1995].;

- Sub-systems (modules) implement one or a few functional elements in their entirety
- The interactions (interfaces) between sub-systems (modules) are well defined and are generally fundamental to the primary functions of the product

Miller [2001] uses the domain theory to describe modularisation as mapping between the different domains. If the organs are not intermingled in each other it becomes easier to split different functions in different physical subsystems of the product.

Module

The sub-systems in a modular product architecture are referred to as modules. One of the strongest explanations of the idea of a module is provided by Baldwin & Clark [2000]; A module is *a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units*. This is actually the core of modularization, because the split between generic and variable characteristics is possible due to the weak integration between the elements and units. This also enables interchangeably for upgrading, differentiation or other purposes.

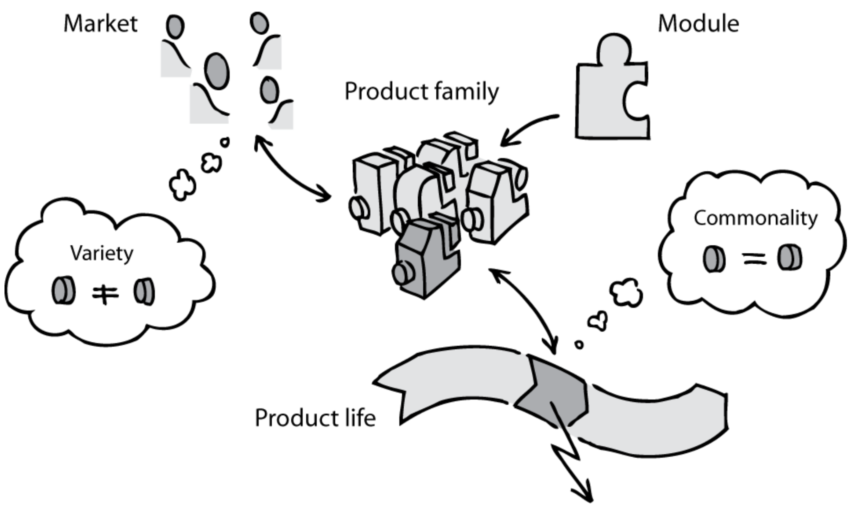

Figure 3.15. *A module is introduced with the intention of achieving a desired effect in the product(s)' meeting with one or more of the product life phase systems.*

The purpose or intention of a module is another very important aspect that separates the module from an ordinary subassembly. Erixon [1998] provides yet another definition of a module. He says that a module is *a decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific reasons*. The company specific reasons are referred to as module drivers.

That is, a module is introduced to the product, product family or product assortment architecture with the intention of creating a positive effect in the product's or products' meeting with one or more life phase systems (fig. 3.16.).

Interfaces

Modules are divided by the interfaces. The decomposition described in the module definitions is only possible due to a careful design of interfaces. The ability to replace one module with another without changing the interface on either side is in fact the key to effective creation of product variety. The interfaces often determine the possible configurations within the product architecture and reflect the intention of the platform, whether it is efficient production, easy upgrade of products, easy service of products, etc.

Product platforms in relation to this research

Product platforms are particular relevant in relation to assessing a product families performance regarding effective and efficient creating of the desired product variety, because assessing the existing product family is natural first step in developing a product platform, which are to substitute and/or supplement the existing products'. And the diagnosis and proposed remedies of such an assessment are very likely to contain elements from the field of multi-product development.

Also, product platforms are a recognised means to create product variety effectively and efficiently. The conceptual framework that lies behind platform-based product development and identification of product platform potential is consequently relevant to this research work.

In relation to this research work, the modularisation principle makes it possible for some parts of the product to be held constant and standardised and others held free to vary, thus enabling the possibility of a co-optimisation of product variety and commonality at the same time.

3.4. Lean philosophy

Lean is a rephrased version of a 30 years old production paradigm from Japan, referred to as the Toyota Production System, TPS [Womack et al., 1990]. It was founded at Toyota and gradually developed to be the Japanese counterpart to the mass production paradigm invented by Henry Ford. Lean refers to a slim or thin value creation process in which a minimum of resources is spent to provide customer value as efficiently and effectively as possible.

Lean has been a major topic in manufacturing industries in the past decades. Lean is originally a manufacturing management paradigm but has evolved into a general process management and optimisation philosophy. The term lean is now associated with many different fields other than mechanical manufacturing plants, such as hospitals and pharmaceutical industries and has also grown into other functional disciplines giving way for new terms like lean accounting and lean product development.

The mindset and tool development of this project has strong links to lean due to this waste/variety correlation, which is why this section will cover a short description of lean and an elaboration how it is related to this research.

3.4.1. The concept of value

Value is a very important aspect in lean, yet it perhaps also one of the more abstract terms in within the paradigm. Value is defined by the customer and is not absolute or constant. It may change with external factors.

The classical example is a litre of water that may be seen as a commodity by a typical citizen in a western city, whereas that same customer would value the litre much higher he/she if had spent two days in a desert without water.

In short value represents the customer's expectations to the product in terms of functionality, delivery time and delivery place. Lifetime, duration, reliability etc. are also factors to include. That is, value is a more broad term depicting the sum of customer's perception of the product and its features as well as the service that comes with the product (should there be one) and the features of that service.

Truly understanding the needs and wants of the customer and appreciate what the customers are willing to pay for, their expectations to delivery performance etc. is not as easy as it may sound.

Lean production is basically concerned with limiting the amount of non value-adding activities in the production. Non value-adding activities are referred to as *waste*.

3.4.2. The concept of waste

The core aspect of lean is a constant and ongoing focus on customer value – what does the customer want – and a likewise constant focus on eliminating waste, which is considered to be those activities and processes that do not add value to the customer.

At Toyota the term *muda* is used to describe waste, and so muda is often mentioned in relation to optimisation and waste removal [Ohno, 1998].

Muda

Traditionally, lean researchers and consultants operate with a total of eight forms of waste. The first seven where formulated at Toyota [Ohno, 1988] and the last was added by Womack & Jones [2003];

1. *Overproduction also known as faster-than-necessary pace*
   Producing more than the customer wants creates many of the other waste forms, as components and/or subassemblies will pile up throughout the production line and finally end up at a stock with finished goods without sufficient demand
2. *Waiting*
   Waiting is waste. Waiting is a waste of time and resources and often occurs when different processes are running out of sync.
3. *Transport also known as conveyance*
   Transport is waste. Moving objects between different production lines or even production sites is waste. Not only is it a waste of time and resources. It also increased the change of damage in accidents and mistaking one batch or site from another etc.
4. *Inappropriate processing*
   Any non value adding process is regarded as waste. Whether it is due to process capabilities, delicate process characteristics or the lack of tools and competencies it will add to the amount of waste in the organisation.
5. *Unnecessary inventory also known as excess stock*
   Excess stock can be a result of minimum stock levels that are too high or simply the fact that two or more consecutive processes are split for some reason and there is a stock put in between. It may be stocked for organisational purposes or geographical reasons or due to the nature of the production planning. Items on stock get outdated, damaged, lost, forgotten etc. Stocks are also excellent to hide the inefficiencies of a production line. In particular slow change over times in production lines are hidden when stocking. Stock takes up space and ties financial resources.
6. *Unnecessary motion*
   Any motion of people's bodies or production equipment is non value adding. Walking around, grapping tools, preparing for a particular position or preparing the production line for a new product variant without adding value is waste
7. *Defects also known as correction of mistakes*
   An important idea in lean is to do things right the first time. Any error and any activity searching for errors is in fact waste, as the error should never have been there in the first place.
8. *Wrong product or service design – that is not meeting the expectations of the customers*
   This last addition is actually a very obvious form of waste. If the whole enterprise is doings its best to get a failure proof product through to the customer in time at the right place, and the product then fails to satisfy the needs of the customer, a lot of activities where in fact waste.

Lean practitioners further divide waste in two overall types, in which the above eight forms may belong depending on the situation;

- *Type I waste*
  Necessary but non value-adding activities
- *Type II waste*
  Non necessary and non value-adding activities

Many waste forms are of type I and for some reason necessary and not a subject to the first optimisation attempts. They can be the result of a specific process capability. Type II waste is on the other hand the focus of any initial optimisation attempts as there is no reason for the existence of it and there is no value arising from it.

Value stream

Womack & Jones' [2003] definition of the value stream is as follows;

"The value stream is the subset of all the specific actions required to bring a specific product through the three critical management tasks of any business: the problem-solving task running from concept through detailed design and engineering to production launch, the information management task running from order-taking through detailed scheduling to delivery, and the physical transformation task proceeding, from raw materials to a finished product in the hands of the customer".

This definition has got three basic elements:

1. A product idea as it transforms from a sketchy concept to a detailed design ready for production
2. Information as it migrates through the value chain (in Porter's definition [Porter, 1985])
3. The physical product passing through the supply chain

Flow

Creating flow is one of the counterintuitive principles of lean. Normally, humans tend to organise things in batches. The difference between a batch process and a single-piece flow is illustrated by the bulk mailing example in figure 3.16.

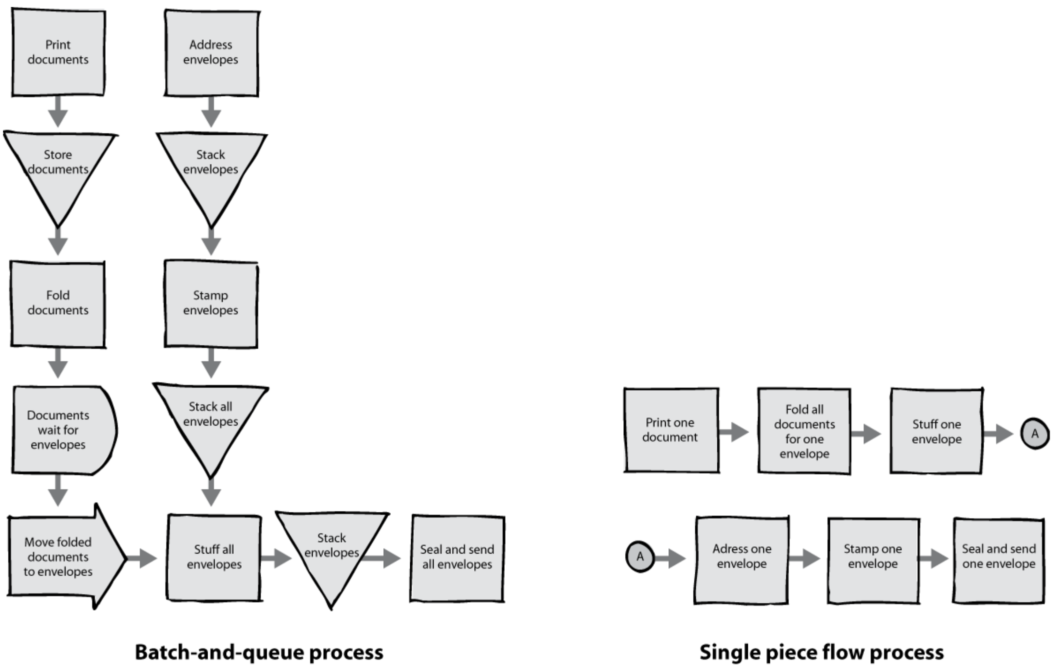

Figure 3.16. *The difference between a batch-and-queue (left) and the coherent single-piece flow (right) process illustrated using a bulk mailing process as example [Sayer, 2007].*

The idea behind creating flow is that the process is faster, requires less resources and a minimum of money is tied up in inventory. The end-objective of flow thinking is to eliminate all stoppages in the production process [Womack & Jones, 2003].

Push and pull

Rather than planning the production, putting the products in a inventory for finished goods and hope than some customer might show up one day and by the products, lean calls for a pull based production, in which a large part of the activities within the company happens on demand. This is an interface with lean and postponement, as a postponement strategy will enable the company to put its order entry point closer to the customer, provided that the lead time of the activities after the order entry point and the flexibility of the production set up is sufficient. The concepts of push and pull are illustrated in figure 3.17.

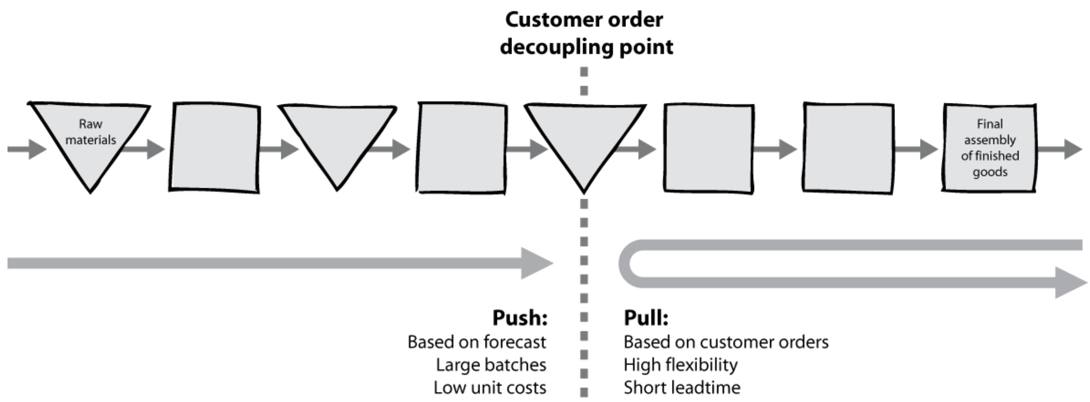

Figure 3.17. *The concepts of push and pull. Push-based activities is planned according to forecasts and inventory levels. Pull-based activities is controlled by customer and sales orders.*

The concepts of push and pull are closely related to the postponement strategy (fig.). Basically, all activities that occur before the customer order decoupling point are planned according to forecasts and inventory levels, i.e. push, all subsequent activities are postponed and should only be triggered by customer order, i.e. pull.

The lean change process

Lean is not implemented over night as a new management scheme; rather, it is a new business culture that gradually transforms a company into what may be called a lean enterprise.

Lean is an ongoing change process. In the beginning it may result in some major changes of a factory layout or the working pattern in a development department. Later on it gradually changes to a process of incremental improvements with employees seeking a potential in their every day working life.

There are five overall steps in a lean change process [Womack & Jones, 2003];

1. Specify value
2. Identify the value stream
3. Create flow
4. Create pull
5. Strive for perfection

The final step of the lean change process is the point that it never stops - there is no final step. Instead, employees at all levels are encouraged, through a mindset and a set of tools and working patterns, to constantly seek improvement potentials.

Lean philosophy in relation to this research

The idea of waste in a product family has originated in several research fields, but the lean paradigm contains a very stringent formulation of waste, which is useful in this work. Although, the eight types of waste that is defined in lean production cannot be directly applied, the concept of waste and elimination of waste is very useful.

Furthermore, linking the concepts of value stream, flow and push to the theory of dispositions is assumed to lead to better alignment of the products' design and the production setup.

Basically, the lean philosophy brings a mindset that has proved useful in the production paradigm to assess production facilities. It is assumed that similar mindset can be applied when assessing product design and product families as is the case in this research work.

3.5. Conclusion

This part of the thesis covers the fundamental theoretical background that forms the basis of the research work. It has described three main areas;

- Engineering design
- Multi-product development
- Lean philosophy

The engineering design research field is the basic starting point for the whole work as I have my personal background within that area. The section presents the general theories and perceptions of products that are relevant to the work.

Multi-product development stresses the importance and potential of making decisions about product families instead of making decision about single products. Decision-making at product family level is necessary if achieve the benefits from commonality effects when deriving the desired product variety.

Lean is a mainly manufacturing oriented paradigm, but it has a very strong formulation of waste and waste removal. When the ideas of waste forms and waste types are brought in to a product design context, the notion of waste becomes very handy in the sense that many design dispositions made in development of a product family are drivers for some of the waste forms.

The actual model development and detailed aspects in the prescriptive study is based on and benchmarked against more tangible tools and methods (from all three areas), which are chosen with regards to the model requirements established in the following part 4, 'Requirements'. These models and tools are then presented in part 5, 'State-of-the-art product family assessment'.

Part 4

Requirements

This part of the thesis has the objective of presenting the requirements for the developed support that is to be used for assessing product families. That is, the findings in the descriptive study (I) in the form of a reference model, plus the additional experiences made in the subsequent prescriptive work.

Finally, the identified requirements are described in detail to serve as guidance for the development of the tool and as benchmark for the concluding evaluation of the tool.

4.1. Reference model

As mentioned earlier the outcome of the introductory descriptive study (I) is normally a so-called *reference model* [Blessing & Chakrabarti, 2002]. This model is illustrated in figure 4.1.

The model is based on observations from three workshops at Danfoss AC together with a review of relevant literature. Following observations during the prescriptive work is not implemented in the model shown in figure 4.1., but merely commented upon if relevant and included in the subsequent listing of the requirements to the supporting tool developed in the research work at hand.

The purpose of the reference model is to describe the network of factors that influence the success criteria so that focus can be directed towards affecting the factors that are most likely to secure the success of the research.

The reference model has its starting point in the measurable criterion – in this case: '*decision foundation*' – and the subsequent question: 'what makes a good decision foundation, then?'

In the following I will account for the elements and the interrelations in the reference model, and the limits of the model (this assessment of the reference model is done in sections one by one, organised in the sections that is found most appropriate and manageable).

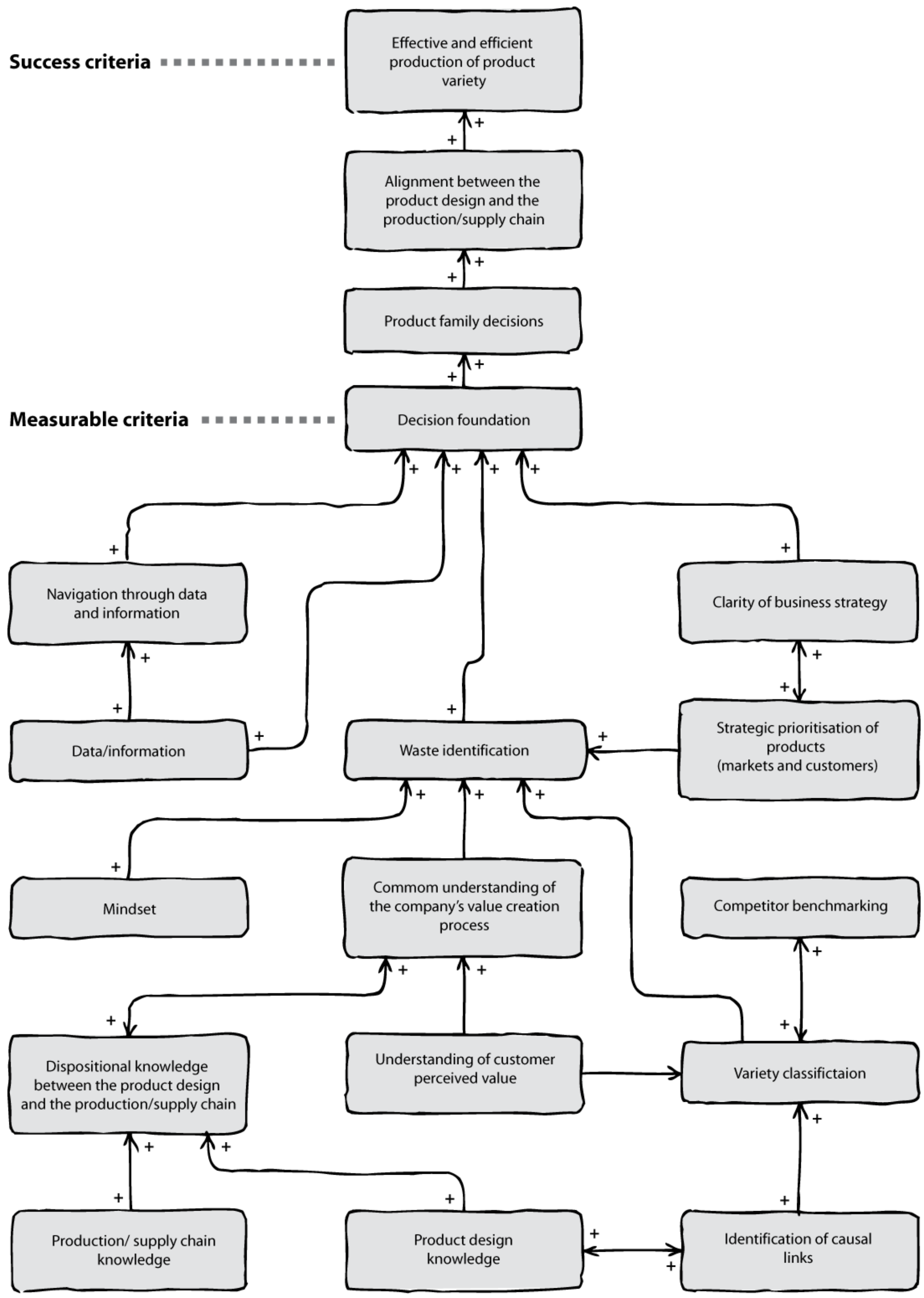

Figure 4.1. *The reference model describes the influencing factors and their interrelations as they are identified in the descriptive study (I) by the means of observations and literature review. The reference model is used to focus the research work in the direction that is most likely to induce success [Blessing & Chakrabarti, 2002].*

Reference model - Section 1

This section (fig. 4.2.) of the reference model describes the dilemma of having all the relevant information and still managing to navigate through this information (i.e. having enough facts to support decisions but so many details that it disturbs the general understanding.

The three workshops that was carried out during the descriptive study (I) (section 2.5.2.) showed that as the participants became more acquainted to the PFMP tool they were capable of navigating through more data, and retrieve detailed information relatively fast, which enabled them to clarify most simple matters of dispute in a few seconds. According to the participants' assertion such matters could usually put the decision-making process on hold for days or weeks until the necessary information was dug up, new meetings was planned, etc.

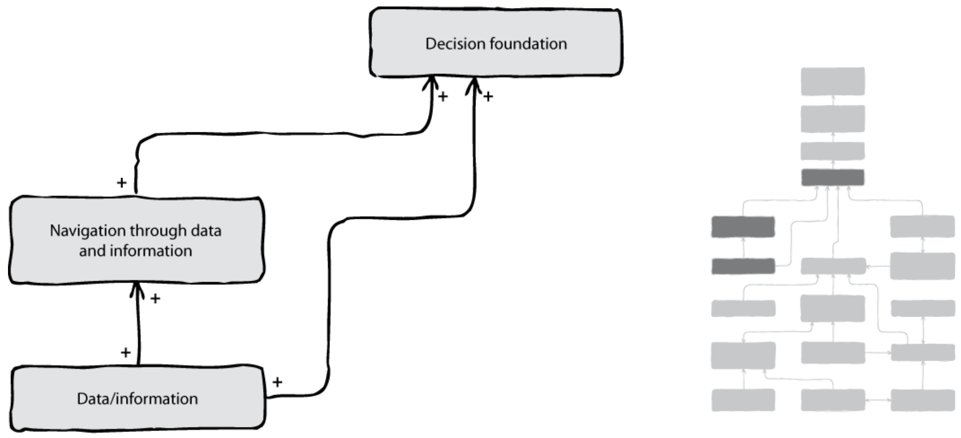

Figure 4.2. *This section of the reference model that describes the dilemma of having enough detailed information available to make well-founded decision and still being able to navigate through this information without being overwhelmed. In lower right corner it is shown the position in the reference model of the present section.*

In even worse cases such unresolved matters led to indisputable arguments, because some experts make unfounded statements from the top of his/her head – e.g. a sales person saying: *"We cannot discontinue this product because it is sold to a very important customer"*. Such a statement can hardly be debated without substantial evidence, and decisions must then rely on the expert's statement, or the decision could be postponed until the statement could be confirmed or rejected.

Avoiding such situations is dependent on having the appropriate amount of data, but also having the relevant details. Other sections of the reference model describe what information is relevant to have in order to improve the decision foundation.

Reference model - Section 2

The section illustrated in figure 4.3. has more focus on what information is needed to support the decision process.

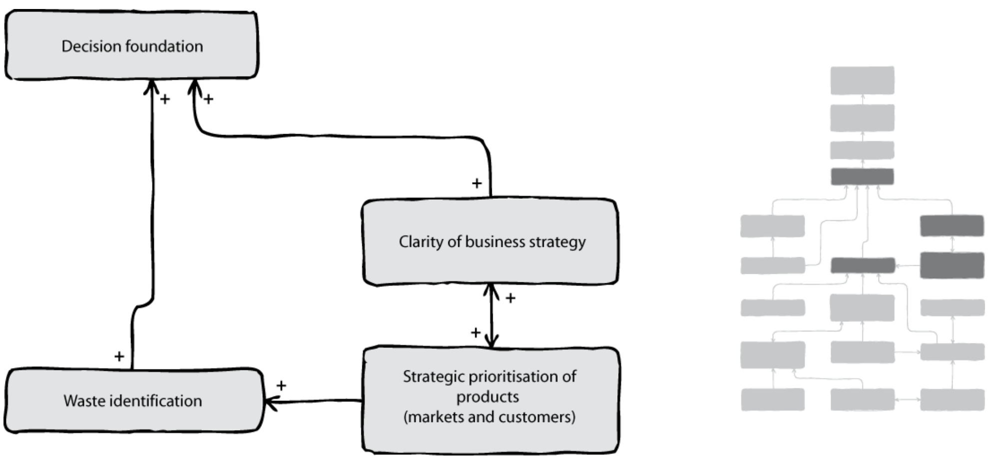

Figure 4.3. *This section of the reference model that describes the need for having a clearly formulated strategy, including identification of strategically important markets and customers, in order to make decisions about the product family appose to making decisions about single products . In lower right corner it is shown the position in the reference model of the present section.*

What information is relevant is of course highly dependent on what kind of decisions you want to make. In this research, focus is on decisions about re-design of the products in order to achieve more effective production of the needed product variety. Using the mindset behind lean production the objective of the decisions is to eliminate waste [Womack & Jones, 2003], i.e. eliminate all activities that do not provide any value to the customer. First step in doing so is to recognise and identify the potential waste.

Waste is according to the philosophy of lean manufacturing defined as anything that does not add value to the customer - It could also be defined as anything the customer is unwilling to pay for [Womack, 2003]. Lean deals with the reduction or elimination of many types of waste with lowest cost and customer perceived quality as driving forces - especially with focus on surplus activities connected to the production of the products.

Literature on lean manufacturing often distinguishes between the two terms [Epply, 2008]:

- Adding value to the customer
- Adding value to the product

The motivation for this distinction is that although something might improve the products performance in some sense, looking at the situation objectively, it may not be valued by the customer, because it was not what he/she was looking for. He/she will not be willing to pay a premium to have a more valuable product and the added extras are actually a form of waste.

In connection to production of product variety it must also be relevant to ask if a specific product variant or product feature adds value to the business. Product variety could for example be generated with an eye to price differentiate products, optimise self space in the supermarket, etc. [Wind, 1982], [Kotler & Keller, 2006]. In such cases the product variety adds no value directly to the customer but it adds value to the business as such.

Nielsen [2008] argues that decisions at this level (i.e. product family level) often become very strategic and should be closely aligned to the business strategy. For one thing, the lack of applicable economic models makes it virtually impossible to substantiate platform initiatives economically. Wide-ranging decisions of this nature will predominantly be based on conviction, but indeed with as much supporting knowledge as possible.

This is in compliance with the observations made in the workshops. In several occasions participants searched for guidance in the business strategy, and in a few cases they referred to the business strategy in their argumentation. Evidently the business strategy was not announced or formulated clearly enough, in the sense that the participating employees in the workshop had somewhat different interpretations of the overall business strategy. The strategy should act as guidance for the employees, but if there is doubt about the strategy it becomes unusable and trivial.

One specific input from the business strategy the participants in the workshop repeatedly asked for was help to prioritise the different markets and customers (the latter being less relevant in the consumer market) and identify the relevant products and/or features. Knowledge about the strategic important market segments and customers is in some cases essential to determine whether a product is adding value to the business or not. If it does not provide value it can by definition be regarded as waste.

Occasions similar to the case mentioned earlier where a sales person obstruct the decision-making process by proclaiming a product "strategically important" has been observed in all three workshops and also during the subsequent work in the prescriptive study. Such situations can become less frequent if the so-called strategically important products, features, etc. are explicitly identified. Prioritisation of market segments and customers is a prerequisite to identify which products fall into that category - if it is not declared clearly what customers and what market have high priority it is simply not feasible do identify the relevant product, features, etc.

Reference model - Section 3

The section illustrated in figure 4.4. has focus on describing how identification of potential waste can be improved by having an understanding of the value creation process and by distinguishing between different kinds of variety.

To understand and identify potential waste it is a fundamental requirement to have a basic understanding of the value stream. The value stream is the set of all the specific actions required to bring a specific product (service and/or good) through the three critical tasks of any business: the *problem-solving task* running from concept through detailed design and engineering to production launch, the *information management task* running from order-taking through detailed scheduling to delivery, and the *physical transformation task* proceeding from raw materials to finished product in the hands of the customer [Womack & Jones, 2003].

Basically, the value stream is the process that should be optimised for effective production of product variety by the elimination of waste.

Again, the participants showed great uncertainty and diffused interpretations of how the company provides value to the customers, and also what value they provide. Typically, their interpretations are based on detailed knowledge in the individual's field of expertise together with a hotchpotch of isolated events and pieces of information they have encountered by coincidence in their daily work. Clearly, the workshop participants lacked a common understanding of the value creation process and this led to many discussions.

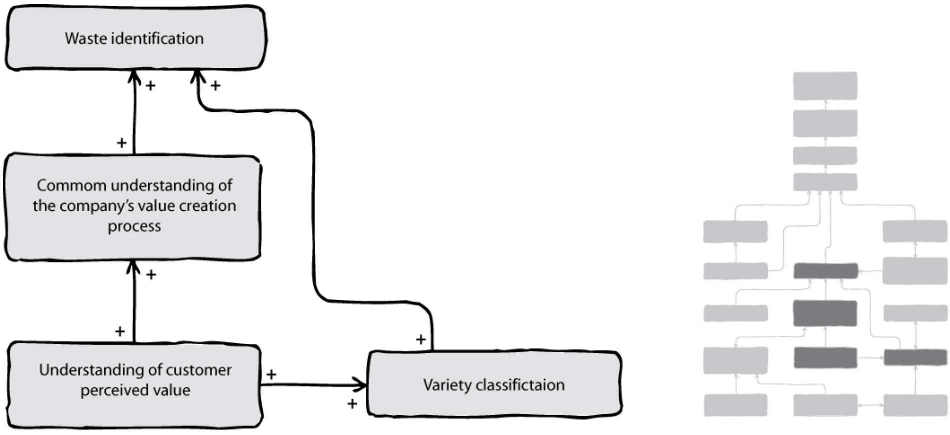

Figure 4.4. *This section of the reference model that describes the need for having a basic understanding of the concept of customer perceived value, both in relation to the value creation process (i.e. production) and variety in the product family. In upper right corner it is shown the position in the reference model of the present section.*

What the customers perceive as value adding was also subject for many discussions. Understanding customer perceived value is a critical prerequisite to understand the value creation process properly. Without a common understanding of the value creation process and an understanding of what the customer consider as being value-adding identification of waste consequently becomes difficult, i.e. if you cannot agree on what adds value you can most likely not agree on what does not add value either.

In relation to analysis of waste in the product family the optimal product variety becomes a key factor. The participants questioned whether specific product variants or product features were actually adding value directly to the customers or in any other way to the business as such. Whether or not a product adds value to the customer can be answered by having an understanding of the customer's perception of value. If it does not add value, it can by definition be perceived as waste, but whether or not it adds value to the business is another and more complicated question.

Reference model - Section 4

The section of the reference model as illustrated in figure 4.5. describes the most critical of the identified factors that can help determine whether certain variety adds value to the business or not.

Causal links can be interpreted as a way to translate the customer need into a physical product design. Causal links tell how product features are realised in the product by one or more of organs, which again are realised by physical assemblies and parts, and vice versa how parts and assemblies contribute to the realisation of organs that contribute to the realisation of product features [Harlou, 2006].

The Danfoss AC case showed that causal links are not documented in any formal way, meaning that designers in most cases can't give account for a specific design except if he/she was the original creator of the design. A small investigation into this revealed, to Danfoss AC's surprise, several examples of designs in their product family that basically served the same purpose and could substitute one another, typically caused by acquisition of competing businesses or lack of awareness about what the colleagues are doing or have done.

An understanding of the causal links is necessary to determine whether a specific part, assembly or organ is adding any value, and therefore is a critical prerequisite to distinguish between value-adding, non value-adding and necessary variety.

A basic understanding of the design and the structure of the products is naturally closely connected to understanding causal links. It would be absurd to discuss causal links without knowing what basic parts, assemblies, organs etc. are included in the products and how they are interrelated. Likewise, a better understanding of the causal links may necessarily enhance the understanding of the reasoning behind the structure of the products [Harlou, 2006], [Mortensen, 2000].

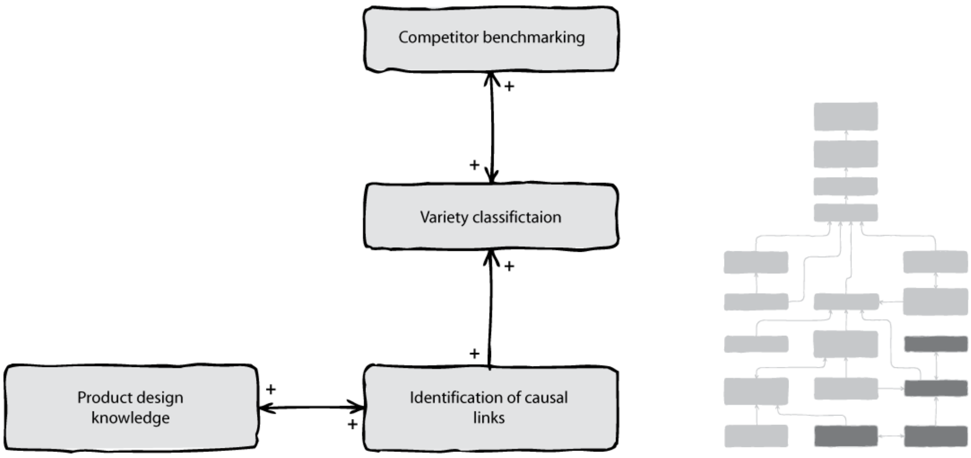

Figure 4.5. *This section of the reference model describes that identification of value adding and non-value adding variety is dependent on identification of causal links (i.e. identification of how product features are realised in the products), and furthermore an understanding of the products' structure. To the upper left is shown the position in the reference model of the present section.*

The case study also showed that another reason for appointing variety as valuable is related to the competitors and their product assortments, in the sense that certain products, features etc. could serve the purpose of differentiating a company from its competitors or the purpose of filling a gap in the product family compared to the competitors' product assortments. Besides, it is generally of great value to keep your business benchmarked against the competition [Kotler & Keller, 2006].

Reference model - Section 5

The section illustrated in figure 4.6. has its starting point in the value creation process of the company.

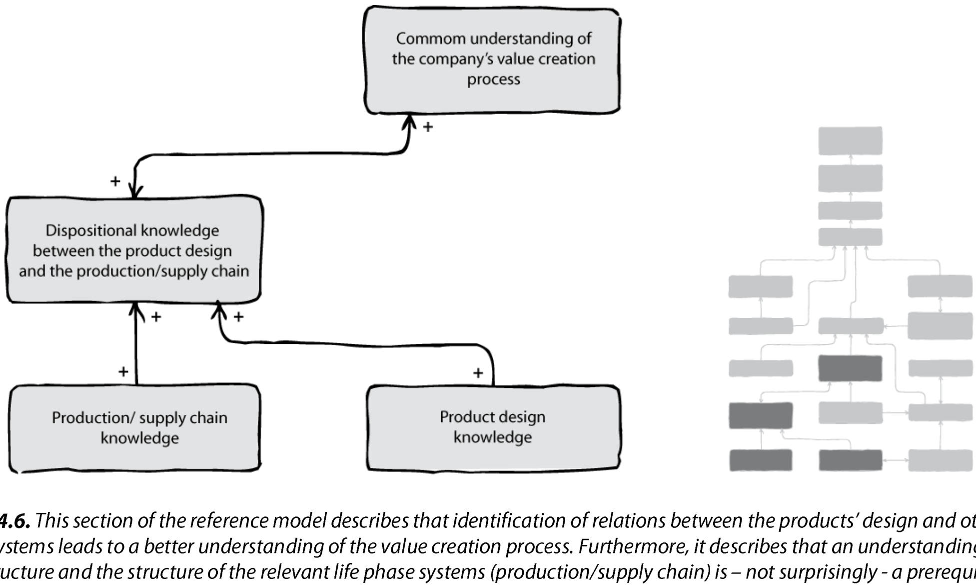

Figure 4.6. *This section of the reference model describes that identification of relations between the products' design and other life phase systems leads to a better understanding of the value creation process. Furthermore, it describes that an understanding of the product structure and the structure of the relevant life phase systems (production/supply chain) is – not surprisingly - a prerequisite for an identification of the relations in between. To the right is shown the position in the reference model of the present section.*

According to theory of dispositions [Olesen, 1992] the overall performance of the product (i.e. product family in this case) is determined by the fit between the product design and the life phase systems.

In manufacturing companies relevant to this research the companies provide value to the customer primarily by supplying physical artefacts (i.e. products). Though, after sales service agreements, technical support etc. is of some importance, the value creation process is mainly concerned with the actual production of the physical artefacts.

For these reasons the performance of the product family and the value creation process is especially dependent on the fit between the products' design and the life phase system related to production of the products. Consequently, focus should be on understanding the product structure and the production/supply chain structure with the intension to understand the relations between them.

Reference model - Section 6

The final section (fig. 4.7.) is directed to the decision maker and the user of the support developed in this research work.

It transpired from the workshops that most of the participants did not fully comprehend the concept of waste or the cost of complexity, meaning that they had difficulties in identifying potential waste apart from the most obvious cases.

To accommodate this situation the decision makers should be infused with the relevant mindset, e.g. by the means of educational seminars. In relation to identification of potential waste a basic understanding of the concept of commonality appear to be very useful.

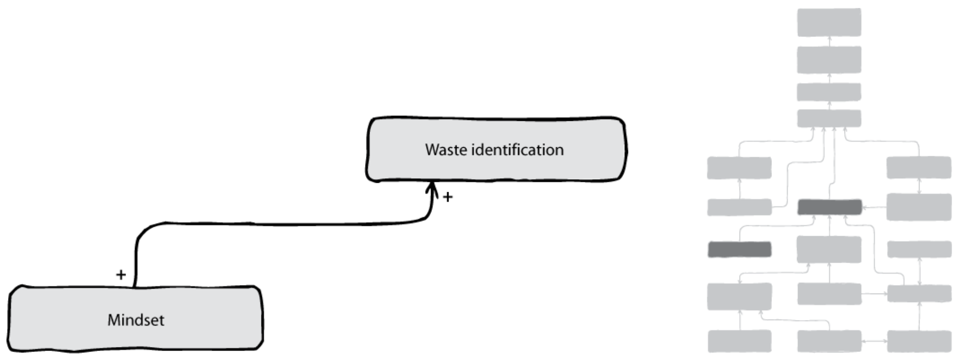

Figure 4.7. *This section of the reference model simply describes that those who are to identify potential waste in the product family are required to have a certain mindset in order to do so (e.g. understand the concepts of waste and commonality). To the right is shown the position in the reference model of the present section.*

4.1.1. Conclusion on the reference model

First and foremost it is important to note that this model is not an accurate rendering of any definitive truth but merely a snapshot of the researchers understanding (at a given time) of relations between different factors that influence the objective of this research. Furthermore, the model is based on an individual interpretation of a sequence of events and would most likely look slightly different if someone else with another purpose and/or background made a reference model from the same empirical basis, but still it serves as a good model to describe how the circumstances are interpreted in this research work.

One thing that should be pointed out from the descriptive study (I) and especially from the work of establishing the reference model, is that this research is in contiguity with many aspects of managing a business enterprise, and therefore support of analysis of product families requires a holistic solution, i.e. a system view approach. That is, having a holistic understanding of transverse relations and trade-offs is much more relevant for the purpose of improving the decision foundation than trying to understand e.g. the product structure alone down to the last detail [O'Connor & Hardenbrook, 2005].

The argumentation for this is based on the assumption that altering one factor separate will only to some extend have positive impact on the overall objective (decision foundation). Additional resources spend on altering a single factor will only have a minimum of or no effect at all (illustrated by the solid grey line in figure 4.8.).

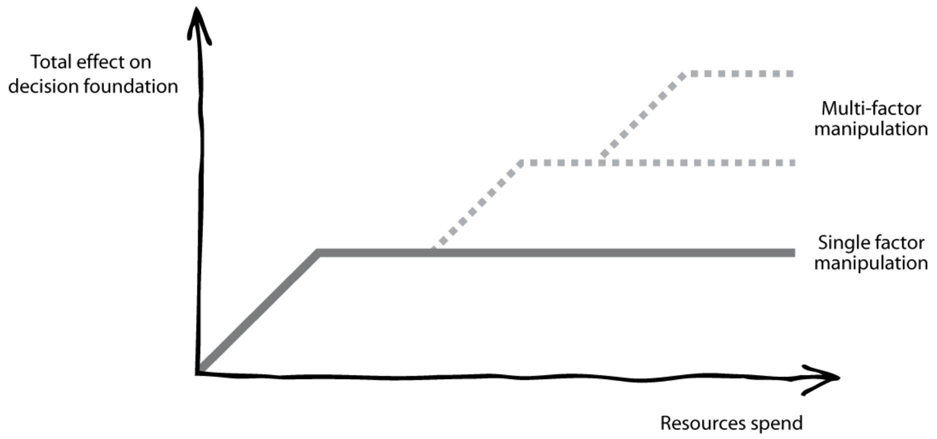

Figure 4.8. *Improving in one direction alone will only have positive effect on the overall aim to a certain extent (solid line). Further resources spent in that direction can be considered as wasted. Improving in multiple directions will permit harvesting even further effects (dotted lines).*

The dotted lines in figure 4.8. illustrates that it is possible to gain further effects, but this is dependent on altering other factors and having a deeper understanding of other aspects.

Consequently, developing a system view approach is giving high priority in the subsequent prescriptive study. This priority is reflected in the so-called impact model, which is described in the following section.

4.2. Impact model

Figure 4.9. illustrates using the reference model how the support developed in this research is intended to influence the measurable criterion. This model is referred to as an *impact model* [Blessing & Chakrabarti, 2002] as it describes how the research work will have impact on the network of influencing factors. The factors that are expected to be addressed by this research are the ones marked in the model using a dark grey colour.

These supposedly addressed factors can be divided into three categories;

1. Factors that are directly addressed by the means of contents of the developed supporting tool:
   - "Identification of products relations to other life phase systems"
   - "Strategic prioritisation of market segments, customers & products"
   - "Identification of different kinds of variety"
   - "Understanding the production/supply chain system"
2. Factors that are addressed through the format of the tool:
   - "Ability to navigate through information"
3. Factors that are addressed through other initiatives:
   - "Mindset (commonality, waste, complexity, etc.)"

As mentioned earlier developing a holistic solution is weighed highly. This is why the research intends to affect relatively many factors to some degree, rather than focus attention on affecting few factors to a greater extent.

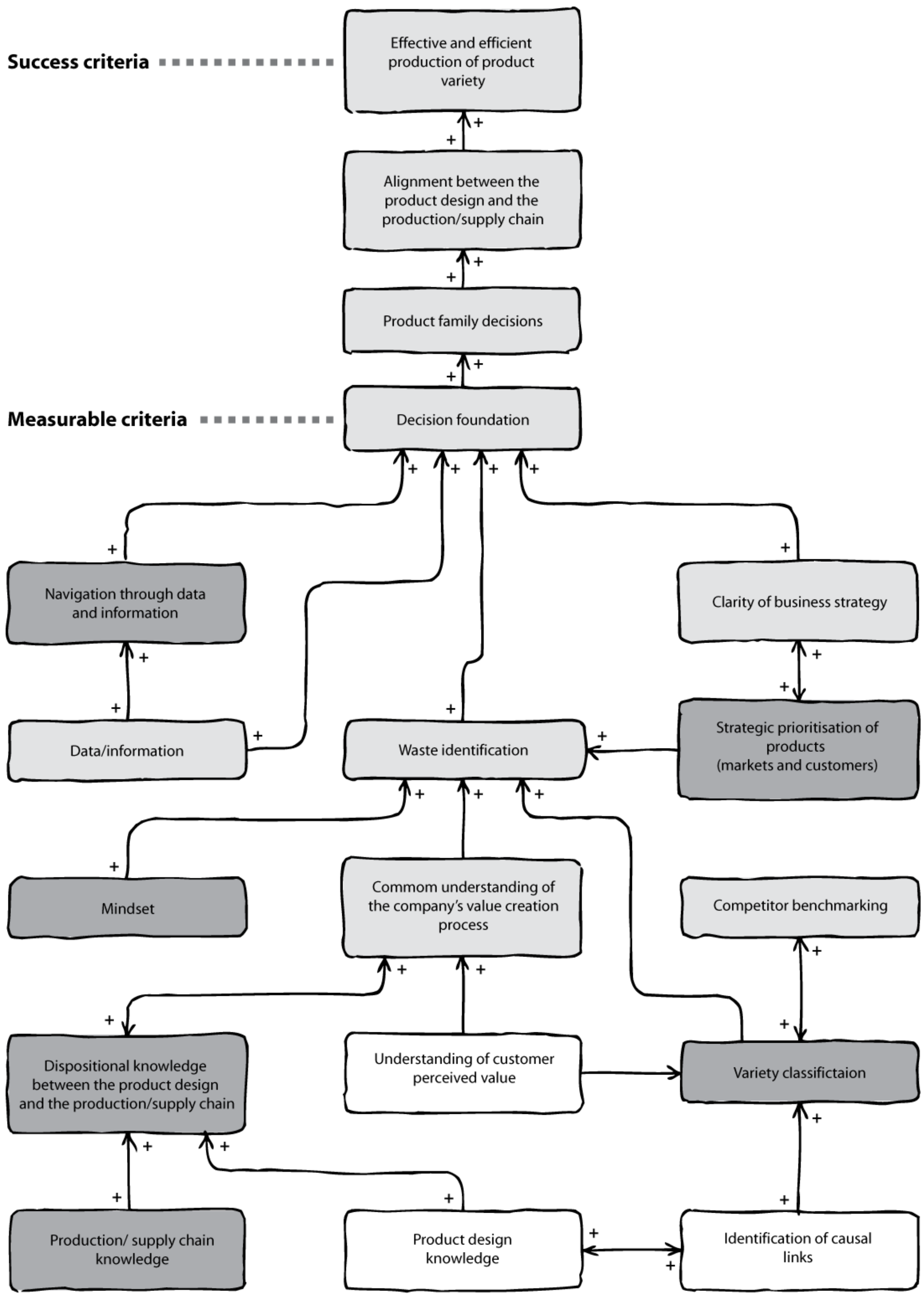

Figure 4.9. *The impact model shows how the research work is intended to have impact on the network of influencing factors described by the reference model. The factors addressed in this research work are marked using a dark grey colour. The factors marked white are the factors that are addressed by the existing PFMP tool.*

In addition, the fact that the support developed in this research is based on the use of the PFMP tool adds further to the impact of the final tool given that use of the existing PFMP tool has impact on the factors marked in figure 4.9. as white with dark contour line.

The factors influenced by the existing PFMP tool are [Harlou, 2006];

- "Understanding the product structure"
- "Understanding customer perceived value"
- "Identification of causal links"

In the following section it is discussed what is required in order to achieve the desired impact on the above appointed factors.

4.3. Requirements

To setup a more applicable basis for the further development of supporting tools it is attempted to formulate what is required by such a tool in order to have the indented impact on the factors, which have been pointed out in the impact model (fig. 4.9.).

In the following these requirements will be explained more thoroughly together with an argumentation for the relevance to the product family analysis, i.e. an indication of what factors the specific requirement is expected to address – and how.

The identification of the list of requirements is primarily a result of observations made in the descriptive study (I) together with a continuous evaluation of the tool during the development in the case study at Danfoss AC (prescriptive study).

Bear in mind that this description encompasses all required elements, including elements that are addressed via the existing PFMP tool or other initiatives, which are not directly linked to the developed support tool, itself.

The set of requirements described in this section composed the basis for the subsequent development of the tool. Not only in the research work done in the Danfoss AC case study both also as basis for the assignment given in the course at the university.

The required described elements in the analysis are:

- Customer perceived product offering
- Value of variety
- Causal links
- Product structure
- Life phase system relations
- Point of variegation
- Production/supply chain system
- Strategic importance
- Critical design issues
- Format of the tool
- Mindset

4.3.1. Customer perceived product offering

An overview of the product variety offered in the market is a fundamental issue when trying to analyse the performance of a product family. Basically we need to answer the question: "*Do we offer the right products?*"

A prerequisite to answer this fundamental question is of course to possess the knowledge of which products are the right ones. How to gain this knowledge is – though it is an interesting question – considered to be a marketing task and therefore outside the scope of this research.

Considering that this knowledge is available the product family should be presented in a way that exposes gaps in the product offering and/or overlapping specifications in particular.

Identifying gaps in the product family is for obvious reasons interesting in relation to gaining market shares. Overlapping product specifications on the other hand is more interesting from a rationalisation perspective. First of all it is not from an efficiency perspective desirable to manufacture two different products having the same specification minded to serve the same market segment. Furthermore this situation can lead to cannibalisation of own markets giving lower volume on both products. Though, addressing different products that have the same specifications towards the same market segment can in some markets be a sound strategy to gain market share [Kotler & Keller, 2006], doing so should be an intentional decision – not an accidental coincidence.

It can seem obvious that a company should not offer products with similar specifications, but many companies struggle not to. Especially in companies that strategically have bought up competing companies and inherit product families more or less similar to their initial product family.

It is crucial that this presentation of the product family is made from a customer's point of view, and show the commercial variation – not technical or physical variation.

4.3.2. Value of variety

First and foremost variety should not be investigated purely from a product point of view. It is just as important to consider variety seen from a production and market point of view. Especially because things from one aspect can be perceived as variety while from another point of view it can be seen as commonality.

In order to identify potential waste and rationalisation potential in the product family it is desirable to be able to characterise variety into 3 different categories:

- Value-adding variety
- Non value-adding variety
- Necessary variety

Value-adding variety

When does variety add value? Variety does normally not directly add value to a single customer because he/she is only interested in the product variant that suits his/her purpose. Value of variety is something that benefit to the business rather than to a customer - product variety is merely a means to better accommodate different customers' perception of value, and hereby increasing market shares.

Considering each variant (product, feature, etc.) separately they should provide some value to the customer in order to justify their existence. The question is, if having fewer variants or maybe only a single variant would serve as a more prosperous business.

Whether or not specific product variety is adding value or not can be a complex question to answer. As an example when focusing solely on a single product it can seem that the company is losing money, but if having a particular product is necessary to gain/keep a large customer buying other more profitable products. Then from a holistic point of view it turns out to be a strategically important and therefore value-adding product variant.

Variety is value-adding when it either direct or indirect is adding value to the business, e.g. by addressing new market segments and open opportunities for gained market share.

Non value-adding variety

Non value-adding variety on the other hand can be described as waste. This variety is either invisible to the customer or not considered as a selection parameter by the customer (i.e. customers do not care whether they get one or the other).

Non value-adding variety does not support gain of market shares or increase of profit.

Necessary variety

Necessary variety can be viewed as being both value-adding and non value-adding. In this case the variety itself is not something customer is interested in. It is a consequence of the dispositions made in the design of the products. It is best illustrated by using an example.

Consider the two welding machines in figure 4.10. In the old product (left) many electrical components are connected by wire. In order to keep track of the different wires when assembling or servicing the product it has been necessary to use different coloured wires. In the new product (right) there are no visible wires, because all electrical components are connected via a single circuit board. The customer is not willing to pay extra for different coloured wires, but the variety in colour is necessary to ease assembly of the product as a consequence of the disposition (multiple circuit boards) made when the product was originally designed. This is considered as necessary variety, i.e. variety that creates benefits other places in the value stream rather than to the customer.

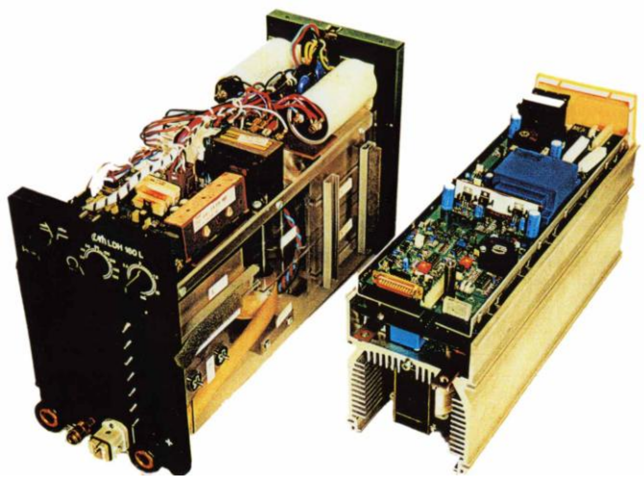

Figure 4.10. *Left: the Migatronic LDH welding machine (before situation), Right: the new Power Module (after situation) [Fabricius, 1994].]*

Fiore [2005] differentiate between two different categories of waste: (a) required waste and (b) pure waste. Required waste represents activities that doesn't meet the criteria for a value-added task but are still necessary to support the creation of the product. Necessary variety can be regarded as a kind of required waste.

As a rule of thumb identified non value-adding and necessary variety is tantamount to identified pure and required waste, respectively, and consequently potential for rationalisation and unexploited commonality.

4.3.3. Causal links

As noted in the above section it can be difficult to classify whether a certain variety is value-adding or not, because the value of variety can be substantiated in many ways and is not necessarily easily visible. Variety must be studied in a context to comment upon the value it is adding. More precisely we need to trace how the diversity in customer demands is translated into product and manufacturing solutions, and vice versa track how diversity in manufacturing processes and product solutions adds value. This is referred to as causal relations and should consequently be a part of the product family analysis.

The chromosome model in figure 3.6. explains causal relations as either *"is realised by"* (pointing downwards) or *"contribute to"* (pointing upwards) relations. The former explaining e.g. how a certain function is realised by physical sub-assemblies and components, the latter explaining e.g. how a physical component contributes to compose certain product functionality.

Understanding the causal relations leads to an understanding of what parts and processes are actually adding value to the customer. Basically the causal relations should be the answer to the question: *"why is this component/process necessary?"* If this question has no meaningful answer then the component/process adds no value. The component/process is therefore redundant and a can consequently be considered as waste.

4.3.4. Product structure

When a product family is to be re-designed it is crucial to have an overview of the design of the product family. A product family can have thousands of product variants, sub-assemblies and parts. The model should enable description of each product variants product structure and basically in some format include the bill-of-material for each and every product in the product family. Simply, printing the bill-of-material for all products is not practical and would not be very helpful. A basic modelling formalism is needed in order to manage such data amounts.

This modelling formalism should primarily enable modelling of variety in the product family and the interrelating constraints, which determines what elements that can be combined to form a complete product.

Variety and classification

Using the term variety implies the presence of some common characteristics in the sense that an element must be classified as something to be denoted as a variant of that class of elements. Classification of elements (product features, parts, sub-assemblies, etc.) is an important tool in dealing with complexity. Classification means to group something according to similarity in structure or behaviour. Finding the most suitable way to classify objects is an iterative process, since it all depends on your viewpoint (e.g. a group of cars could be classified by colour, brand, number of seats, etc.).

Constraints

Constraints in the product family are limitations to the flexibility of combining elements (components, sub-assemblies, modules, functions etc.) in the attempt to create product variety.

Some elements may be dedicated to create a single product variant. In some situations dedicated solutions can be the right decision. For high volume products it can be economically beneficial to optimise for example a component for manufacturing, use of material, performance, etc. But generally dedicated solutions should be avoided in favour of more flexible solutions. Consequently, it is relevant to understand the constraints in the product family.

Basically, understanding the constraints in the product family is about knowing what elements fit together and which do not.

4.3.5. Life phase system relations

Life phase system relations are used to describe the so-called fit between the products' design and various life phase systems. According to Olesen [1992] the product design predispose to the performance of the product in the meeting with the different life phase systems, meaning that the product design determines e.g. how easily a product can be produced. The importance of design decisions that have impact on the life phase systems is also pointed out by Prasad [1996 & 1997].

DFX (Design for X – 'X' being replaced by e.g. 'A' for assembly or 'M' for manufacture, etc.) design approaches aims at accommodating the product's design to the assembly process, manufacturing process, etc. during the early conceptual phases of the product development [Fabricius, 1994]. The product is in this way designed to be prepared deliberately for the meeting with other life phase system.

Relations between product and production domains should describe the consequences in production of decisions made in the product domain and vice versa the consequences in the product design of decisions made in the production domain (e.g. choice of a specific manufacturing technology).

4.3.6. Point of variegation

When a company wants to offer a wide product range it is normally of interest to postpone the point in the supply chain where the physical parts become dedicated to a certain product variant. This point is noted as the *point of variegation* [Ramdas, 2003 (a) & (b)] .

The point of variegation is an important indicator for how well the product design and the supply chain is aligned, thus also an indicator for a company's ability to produce product variety effectively [Madsen, 2001].

Although, closely related the point of variegation should not be confused with the *customer order decoupling point* (CODP) or *order penetration point* [Michelsen & Pagh, 2002], which is used to denote the point where the customer enter the company and thereby *pulls* the production of a specific product variant. Placing the CODP is purely a strategic decision, whereas the point of variegation is a result of the actual product and production design.

Postponement expresses the intension to put off all activities that follow the CODP and not start these until it from an actual customer order appears which and how many products should be produced [Michelsen & Pagh, 2002]. *Speculation* is described as the opposite of postponement. In this case the company produces products mainly to stock based on forecasts of what they expect the customers to buy and then hope the demand matches the products they have in stock. Fluctuation in customer demands makes this strategy less appealing – the company either misses out on extra sales because the stock level of a specific product variant is not high enough or it wastes resources on producing product variants that are not sold.

The key to effective production of product variety is to postpone the task of differentiating a product for a specific customer until the latest possible point in the supply chain system [Feitzinger & Lee, 2000], i.e. postponing the point of variegation. As a consequence the strategically imposed CODP can be postponed corresponding with advantage.

It is therefore of paramount significance to identify the point of variegation because it can help point the re-design efforts towards postponing the point of variegation.

4.3.7. Supply chain system

Understanding and modelling the supply chain system is relevant for several reasons:

- *Variety*
  Identification of variety – and different kinds of variety - in production and supply chain is just as relevant as identification of variety within the product design. The model should therefore support visualisation of variety.
- *Life phase system relations*
  It can fairly be presumed that having an understanding of the supply chain is a prerequisite to identify relations between the supply chain and the product structure, since it is by comparing the supply chain and product structure that these relations become visible. Hence, the supply chain should be studied with the intension to identify life phase system relations.
- *Point of variegation*
  Modelling of the supply chain can be used to illustrate the point of variegation, i.e. identify when, where and how the task of product differentiation happens.

Furthermore, modelling the supply chain can contribute to a common understanding of the company's value stream.

4.3.8. Strategic importance

When discussing rationalisation it is important to point out that not all elements (products, functions, modules, components etc.) are of same importance to the success of the overall business. Logically, all product variants should be of significance for the business – if not, these product variants should be discontinued.

As discussed earlier product variants can contribute to the overall business in many ways. Some product variants are for instance important due to the number of products sold. Other product variants could be important for strategic reasons (e.g. price differentiating, important customers, flagship products, etc.) [Wind, 1982].

Because the analysis is meant to serve as preparation for the re-design the product family it is also highly relevant to understand how the products, features, functions, etc. should be prioritised in the design process, as the new design should favour the core products and not some peculiar special product.

Thus, the model should enable accentuation of strategically important product variants, features, functions, etc.

4.3.9. Critical design issues

One thing that became apparent during the later stages of the analysis of the solenoid valve product family at Danfoss AC was a need to collect previous sources to claims and other critical design issues that had been encountered during the years.

The incentive to do so was to learn from years of experience and avoid the same mistake twice. This seems very basic, but the fact that Danfoss AC has experienced a high turnover of staff within the engineering department has meant that the existing engineering work force is more or less unaware of critical design issues, which have been encountered earlier than a couple of years ago.

Since scrap in the production is defined as a form of waste [Womack & Jones, 2003] elimination of poor design that causes scrap can be considered as one objective for the re-design process.

4.3.10. Requirements to the format

One of the key assumptions of this research work is that easy access to data can improve the decision foundation and accordingly the decisions that follow.

Locating the needed information in the various ERP, PDM, and CAD systems seem to be too cumbersome, mainly because the user isn't sufficiently qualified or because of lack of discipline when the data is stored. Even if the data is successfully located the system does not facilitate to link the piece of information into a context.

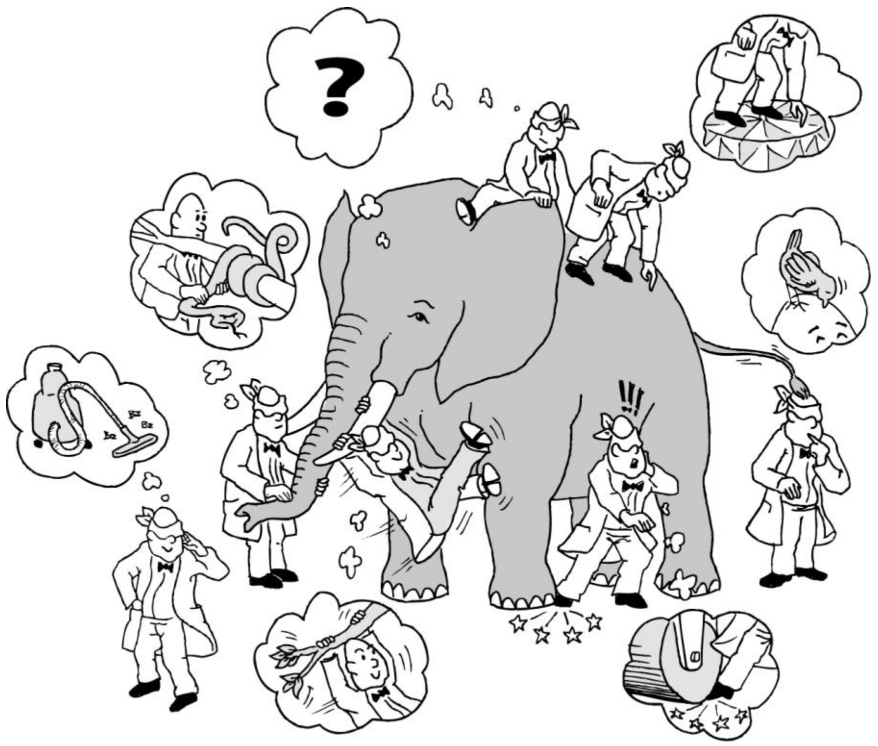

Figure 4.11. *The story is told, that once upon a time in Prague seven learned professors were led in blindfold to an elephant, with a view to describe the elephant afterwards. They came to many astonishing conclusions [Andreasen & Hein, 1987].*

Consider figure 4.11. Scattered information without having a context to relate it to it can easily led to hasty and wrong conclusions [Andreasen & Hein, 1987].

It is important that the model makes it possible to link the different pieces of information to each other [O'Connor & Hardenbrook, 2005]. This entails severe demands to the format of the developed support.

According to Henderson [1999] visual tools (sketches, drawings, etc.) are the basic components of communication for engineers and designers; coordination and conflicts take place over, on, and through drawings. Visual representations are so central that people assembled in meetings wait while individuals fetch drawings from their office or sketch facsimiles on whiteboards.

As the tool developed in this research work should serve as support in meetings, facilitating discussing about rationalisation of the product family, it is presumed that the best result is achieved through the use of a visual representation of the data [McKim, 1980].

4.3.11. Mindset

The final focus area for this research has to do with preparatory education of users of the tool. First and foremost a certain familiarity to the tool is needed by the users in order to be able to navigate and extract the needed information, i.e. learn the codex used to build the model [Henderson, 1999].

Furthermore, visual thought is cognitive activity [Arnheim, 1969] and in order to interpret the data presented in the tool the users should carry a certain mindset, i.e. if the users are to identify for instance waste, they have know what waste is.

That is why it is set as a requirement that the members of the design team (i.e. the users) are trained in the basic concepts of waste, commonality, variety, etc., and that they are also given an introduction to the ideas of product platforms, product architectures, mass customization, modularization, etc.

This part of the requirements will be satisfied by arranging a number of seminars at the company.

Part 5

State-of-the-art product family assessment

The objective of Part 5 is to present the current state-of-the-art product family assessment tools and methods that are presented in literature. The methods and tools are review with respect to the requirements that were established in the Part 4 and with the intension of identifying methods and tools or elements of these that could contribute to the support developed in this research work.

5.1. Review challenges

The following section will present a screening of existing methods and tools that are relevant to the list of requirements presented in Part 4.

The state-of-the-art study in this section has two purposes;

- It has to clarify the limitations of the present research knowledge and working practice and help justify that there is in fact a research contribution in this thesis
- It has to serve as an inspiration for the prescriptive work in the thesis

The reference model in the former section and the resulting list of requirements span a wide range of different aspects. From a literature review point of view, two main research areas will be included in order to keep focus;

- Product development and product structural aspects, i.e. knowing your products
- Production and manufacturing aspects, i.e. knowing the efficiency and effectiveness of the way the products are made

This project takes it starting point in a product development paradigm and expands into the production working field. It does not incorporate marketing aspects from a research point of view, as the contribution does not lie within marketing research. As mentioned in the former chapter, it is a prerequisite for the prescribed tools that the company has got sufficient knowledge on customer demands, segmentation, market trends etc.

There are two challenges when reviewing relevant literature. The first challenge is the fact that this thesis covers the links between the two areas (i.e. life phase system relations) and the alignment of them. The second challenge is the fact that the thesis has its starting point in product development paradigm and consequently a natural stronghold in this field along with a more shallow foundation in the production/supply chain paradigm.

There is not one united body of research dealing with alignment of the two domains and few research communities are working on that broader scale. Most of the available literature has its focus in an either process oriented viewpoint or product design and development oriented viewpoint. Moreover, few consider the aspect re-designing a product family with the intention of limiting complexity and non value-adding activities (i.e. waste). In the search for existing research on the topic of alignment and product family analysis in order to identify methods that both address the product family and the production set up, a natural starting point is to search for tools within product development, operations and supply chain management, and from those two areas extract comparable research work.

In the following section the tools and methods are described one by one including an evaluation of how each method/tool meet the identified requirements.

5.2. Product design & supply chain models

All methods and tools can be placed on a scale ranging from quantitative to qualitative. They are not necessarily one or the other yet some have a strong focus on mathematics, numbers and calculations while others are more qualitative and have the purpose of representing information and thereby enable the viewer to see the get an impression of the problem at hand.

To summarise in a simple way, one may say that;

- *Quantitative approach*
  A quantitative approach presents the results of an analysis in terms of numbers and statistical parameters. The analysis does – to some degree – provide the results directly, the output being numbers based on a rather mathematical working paradigm.
- *Qualitative approach*
  A qualitative approach has a focus on descriptive modelling from which it is possible to interpret a meaning indirectly through the use of specific domain knowledge.

As this work is exploring the advantages of graphical and visual overviews most of the methods in the following sections are of a rather qualitative nature, yet some of them do have quantitative aspects.

In the following I will list those of the methods and tools in the body of research I have found most relevant for this work. First I will go through the relatively product and design oriented methods and later I will list some production/supply chain modelling methods and tools.

Some of the models described in Part 3, 'Frame of reference' are among the list of relevant modelling approaches. They are not described in this section because I have enclosed them in part 3 and regard them as more fundamental for this research than the following tools and models.

5.2.1. QFD – Quality Function Deployment

The Quality Function Deployment is a widely used methodology to capture customer demands and translate them into specific product and production process characteristics [Akao, 2004], [Prasad, 1997]. The focus of this thesis is not the translation of customer demands into product specifications yet the work does deal with the corresponding organisational interface between the marketing and sales organisation on one side and the product development department on the other side, as it deals with the facilitation of decision making on a product family level. Therefore QFD is relevant as it constitutes a semi visual methodology supporting the exchange of information across that barrier.

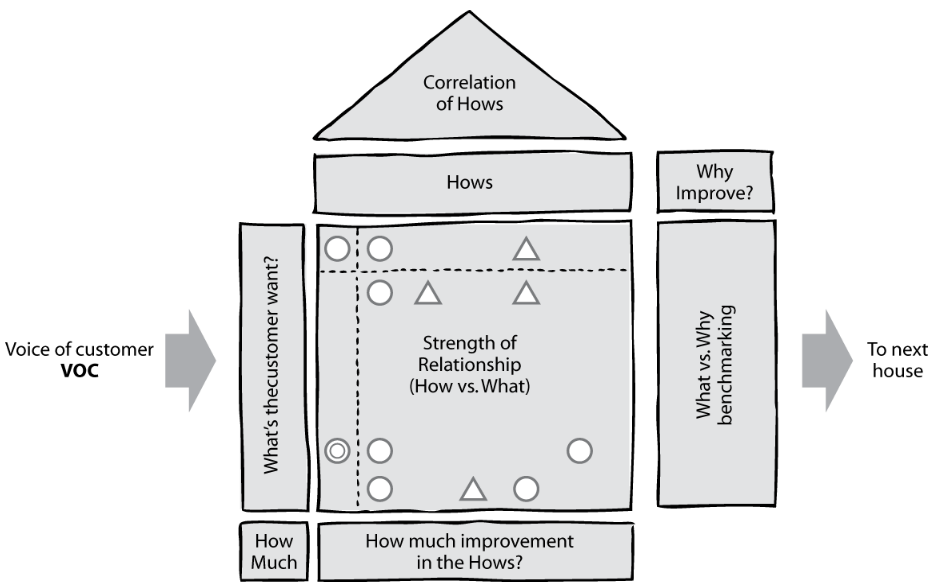

Figure 5.1. *The principal structure of a House of Quality [Akao, 2004].*

The House of Quality (HoQ) illustrated in figure 5.1. plays a central role in the QFD method. The VOC, Voice of Customer, is formulated on the basis of customer surveys, focus groups, the experience in the sales and marketing organisation etc. They form the "What's" in the left part, as rows with different customer demands. Each row continues into the correlation matrix in the centre of the house (The How vs. What). The dependencies are mapped through the use of a scale denoting the strength of relationship from independent to highly dependent. The "Hows" on top of the matrix are then the product features that are needed to satisfy the "What's". If it was a bicycle, for example, a "What" could be the customers desire to sit on the bicycle. A corresponding "How" with a strong relation to that particular demand would naturally be a saddle whereas the gear system would be another "How" that is relatively independent of how the customer wants to sit on the bicycle as it has another main function. The bottom part of the house contains the specifications related to the "Hows", i.e. how soft is the saddle, expressed by a preferably quantitative measure unit and a size.

As illustrated in figure 5.2. a total of four houses cover the path from customer requirements to process controls in a factory.

In the houses inputs are translated to outputs that form inputs for the subsequent house. Through a gradual change in viewpoint one can map the relation between a specific customer need, the design requirements arising from that need, the process characteristics needed, and finally the process capabilities.

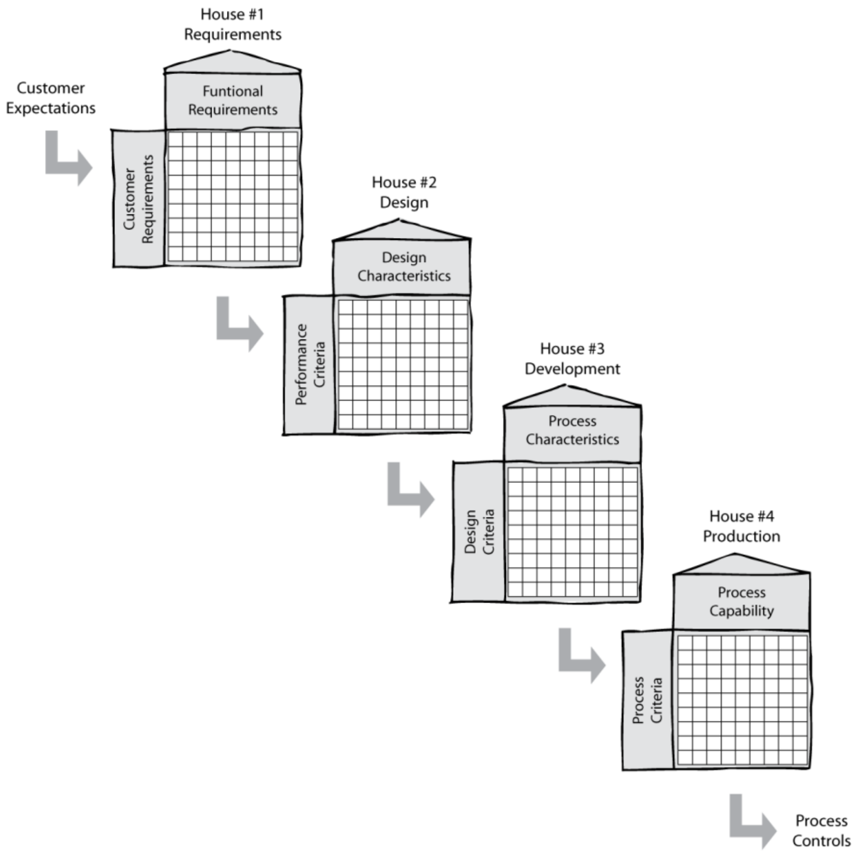

Figure 5.2. *Four consecutive houses of quality transforms the voice of the customer into functional requirements, design characteristics, process characteristics and process capabilities. The output of one house forms the input to the following house.*

Conclusion on the QFD

Large QFD's can hold a substantial amount of information and the correlation matrices may become very large. It may compromise the ability to get an overview. On the other hand it is the strength of the QFD approach that the ability to map complex relations is present.

In relation to the identified requirements the QFD method has its focus on modelling causal links and life phase system relations. The causal links are managed in house 1 and 2, and the life phase system relations are managed in house 3 and 4 (fig. 5.2.). The QFD method focus – as it is also the intention in this research – on relations between the product design and the production system.

Besides the QFD method includes some aspects related to the requirements: customer perceived product offering, product structure, supply chain system, and critical design issues. Though, only to a somewhat limited extend.

The key inadequacy of the QFD method is the fact that the tool is intended to be used for design and re-design of *single* products and does not facilitate handling of variety. This disqualifies the use of the QFD method in relation to re-design of product families as it is, but the method has some aspects that possibly could be applied in the analysis of product families.

Furthermore, the QFD method is not a particular visual model and the size of the matrices in the various houses of quality rapidly expands and it becomes troublesome to navigate the information – no impossible though.

As with many other methods and tools, the process of making the houses is one of the key advantages as it brings together people from different departments (if done correctly). In that respect one may find the process of making the houses more rewarding than the result itself.

5.2.2. MFD - Modular Function Deployment

The modular function deployment (MFD) [Erixon, 1998], [Ericsson & Erixon, 1999] builds largely on the methodology of the QFD and on the formulation of eight so-called *module drivers*, which are explained in the following section. The purpose of MFD is to enable cross functional teams (including mainly marketing, development and production personnel) to create a mapping from the physical structure of the products within an family to the functional structure of those products and to ensure that the functional structure corresponds to the demands of the customers. Again, MFD, like QFD, deals with the organisational interface between sales/marketing and product development.

Figure 5.3. illustrate how the Modular Function Deployment method consists of five consecutive steps, of which the first three are relevant to the scope of this research.

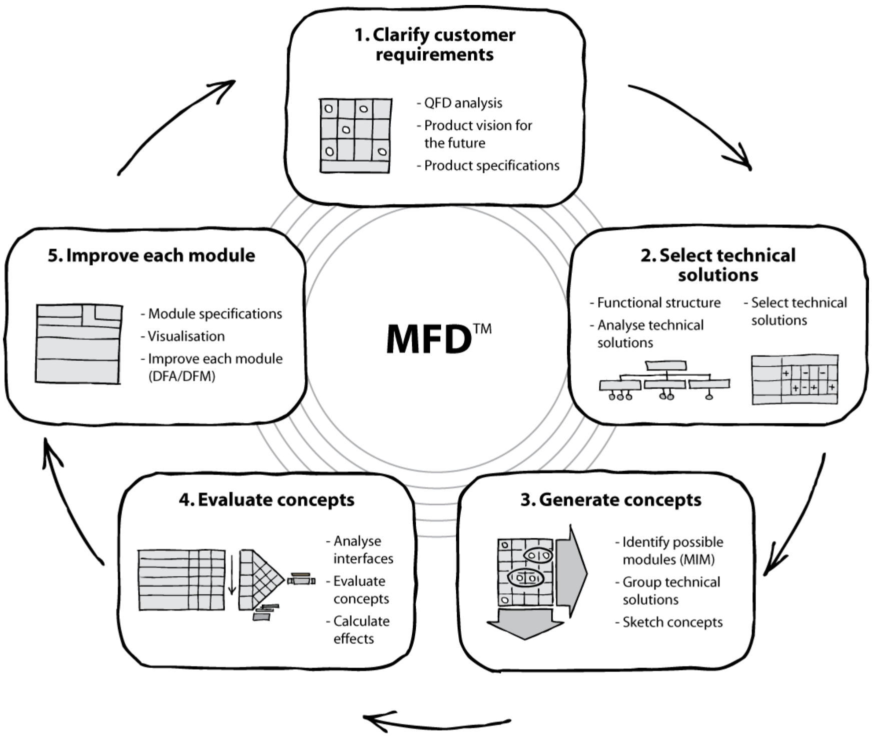

Figure 5.3. *The five steps of the Modular Function Deployment methodology. Customer requirements are mapped to functional criteria and subsystem design characteristics and subsequently forming a physical design in which a modular architecture supports a carefully selected set of modularisation incentives called module drivers.*

The first step resembles that of the first House of Quality in which customer requirements are translated into product features. The second step resembles that of a *function means tree* [Hubka, 1973], in which designers screen a solution space for possible designs to carry the functions needed to support the customer requirements. In the third step concepts are generated on the basis of an evaluation of technical solutions against a list the module drivers. The module drivers are explained shortly in the following section. The fourth and fifth steps are rather traditional product development steps in which concepts are evaluated and modules refined.

Module drivers

The most important aspects in the MFD approach are the so-called module drivers. They are formulated as modularisation incentives, i.e. different reasons to modularise a product family. Some drivers are more related than other drivers and each of them will have different implications on the product design. The following list in figure 5.4. provides a short explanation of the twelve module drivers.

Module driver type	Module driver	Description
Development and design	Carryover	A carryover module is a module used across product generations - i.e. reused in time
	Technology evolution	Technology evolution reflects the preparation for future changes caused by technological changes
	Planned design changes	Planned design changes reflects the preparation for future changes caused by planned design changes
Variance	Different specification	A different specification modularisation approach is used to allow key parameters to be changed in order to change the specifications of a product
	Styling	The overall product function is the same and the modularisation efforts have styling and aesthetics changes as its primary purpose
Manufacturing	Common unit	A common unit module is a module used across product variants - i.e. reused in the product "space"
	Process/organisation	The product is split due to organisational or process related reasons such as a specific production layout or competence driving a natural product split
Quality	Separate testability	Testing each module before the final assembly may lead to improvements in the overall product quality
Purchase	Supplier availability	Some parts of a product may be suitable for outsourcing or readily available, thus forming a natural module
After-sales	Service/maintenance	A service module is a clustering of functions that are prone for wear and tear
	Upgrading	Those functions that are often upgraded can clustered in a module to form a simple way of upgrading without a large part of the product being redesigned
	Recycling	Replacement is also useful for recycling purposes and a subsystem containing expensive materials or potentially dangerous parts may be isolated in a module

Figure 5.4. *A short explanation of the Module drivers. Adopted from [Ericsson & Erixon, 1999].*

The module drivers are used in the Module Indication Matrix (MIM) (fig. 5.5). The MIM is a matrix in which technical solutions are mapped against the module drivers. It is not as such a tool that identifies potential waste, but it does have interesting features. That is, the twelve module drivers state the intention of a wish to create an effect in other life phase system (e.g. making service of the product more effective, improvement product development, etc.) by introducing modules to the product design.

Conclusion on the MFD

The primary strength of the MFD tool in relation to this research is the tools ability to link potential effects in other life phase system to the product structure, i.e. linking the module drivers to the technical solutions in the module indication matrix. On the other hand the MFD method solely deals with identification of potential physical modules. In the quest for deriving product variety more effectively this is but only one means for achieving this.

Although, half of the twelve module drivers are related to more effective generation of product variety the MFD tool does not enable modelling of such variety. Rather the method models the generic product that represents all products in a product family. In figure 5.5. for instance, the module driver 'common unit' scores relatively high, meaning that it is very likely that a common module can be shared among the product variants. The MFD method presumes that all variants in the product family are composed by the same technical solutions, i.e. the products must be relatively similar compared to figure 2.1.

		Technical solution																	
Module driver			Arch assembly (LH,RH)	Arch (2x)	Base weld assembly	Front crossmember	Rear crossmember	Jaw	Lock bar	Jaw pin	Lock bar pin	Pushlink lever assembly	Handle	Cover plate weld assembly	Saddle plate weld assembly	Safety clip bracket	Adjustment stud	Tail gusset	Top plate	Bolt (handle)
	Development and design	Carryover	●			●	●			●	●				●	●	●	●	●	●
		Technical evolution		●	●			●	●			●	●	●						
		Planned design changes																		
	Variance	Different specification		●	○			○					●							
		Styling																		
	Manufacturing	Common unit	●		●	●	●	●	●	●	●	●		●	●	●	●	●	●	●
		Process/organization																		
	Quality	Separate testing																		
	Purchase	Supplier available	○	●		○	○	●	●	●	●	◐	○				○	○		
	After-sales	Service/maintenance		●	◐			●	●	●	●	○	●				○			
		Upgrading																		
		Recycling																		
		Score	19	36	22	19	19	37	36	36	36	22	28	18	18	18	20	19	18	18
		Candidates		X	X			X	X	X	X		X							

● = strong relation (9)
◐ = medium relation (3)
○ = weak relation (1)

Figure 5.5. *An example of a module indication matrix for a fifth wheel for a pulling truck. The technical solutions "arch", "base weld assembly", "jaw", "lock bar", "jaw pin", "lock bar pin", and "handle" have been pointed out as module candidates [Ericsson & Erixon, 1999].*

Having the module drivers – and especially the ones related to product variety (i.e. 'carryover', 'technology evolution', planned design changes', different specification', 'styling' and 'common unit') – in mind when analysing the product family can support identification of improvement potential for a re-designed product family.

5.2.3. DSM - design structure matrix

This approach takes a starting point in the decomposition of a product into components/systems and an identification of interfaces/relations among these (fig. 5.6.) [Pimmler & Eppinger, 1994]. By the use of algorithms, it is possible to encapsulate components into modules or chunks that are closely related to each other from an interaction point of view [Steward, 1981]. This process is referred to as *clustering*. The outcome of a DSM is a proposal for a future modular product architecture.

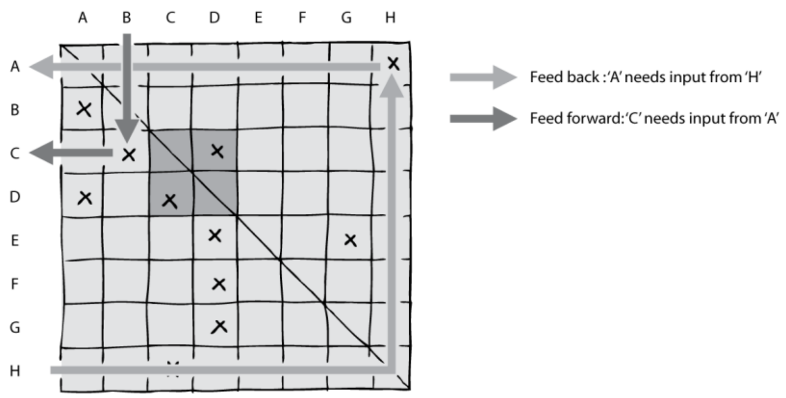

Figure 5.6. *An example of a design structure matrix [Höltta-Otto & De Weck, 2007].*

There are some similarities between the DSM approach and the Modular Indication Matrix provided by the MFD method described above in section '5.2.2. MFD – Modular function deployment'. The main difference is that the subsystems are not mapped against drivers of modularity or other external factors. Instead, they are mapped against each other for correlation purposes, in order to cluster subsystems that are closely interrelated and separate those that are not. The Design Structure Matrix is not a particularly visual model. It does on the other hand have the ability to hold a large amount of information and make it readily available for retrieval.

Conclusion on the DSM

The DSM method is a powerful tool to identify potential modular structures. Unfortunately, the DSM method focuses solely on the interrelation between elements (parts, assemblies, organ, etc.) in the product structure. The DSM does not in any way include considerations regarding life phase system relations or causal links. In this way the DSM method generates a proposal for a modular product structure without regards to what effects are expected or what consequences such modular structure would have in products' meeting with other life phase systems. This is a major disadvantage for the method.

Furthermore, the DSM method is primarily a tool that can be used for re-design of single products and does not support handling of product variety unless they have more or less identical structures (i.e. same part/assemblies and interaction between).

5.2.4. Generic bill-of-material

The generic BOM originate from the assemble-to-order environment [van Veen & Wortmann, 1987]. The end-products typically have a number of features for which a number of options are available to choose from. Not many options are required in order to make the number of combinations (i.e. end-products) enormous. The number of end-products can easily become too large to able to define specific BOM's for every single combination. Furthermore, forecasting, BOM-storage and maintenance become unmanageable.

The generic BOM is a concept that is introduced to enable creation of a specific manufacturing BOM when the customer places an order, by replacing.

The generic BOM is used to describe of related products in one all-embracing model by using generic and specific items.

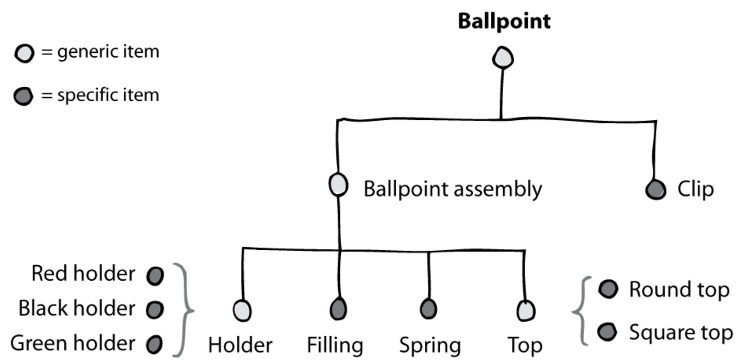

Figure 5.7. *A generic bill-of-material (BOM) describing 6 combinations of ballpoints (end-products) [van Veen & Wortmann, 1987].*

As illustrated in figure 5.7. a generic item can consist of one or more specific and/or generic items. The generic item 'holder' describes the specific items 'red holder', 'black holder' and 'green holder', and the generic item 'top' describes the specific items 'round top' and 'square top'. If the specific items in figure 5.7. can be combined freely the model describes 6 combinations of end-products (ballpoints).

A specific BOM is generated from the generic BOM by replacing the generic items with specific items. When all generic items are replaced by specific items the product is unambiguously defined.

The key to efficient generation of specific BOM's is to link the generic BOM to a set of parameters and parameter values (customer options) in such a way that when a full set of parameter values are obtained then the product is uniquely defined. The ballpoint in figure 5.7. is described by the parameter set *P:{colour, model}*, which have the coherent values *V(colour): {red, black, green}* and *V(model): {round, square}*. The generic BOM is linked to parameter values using boolean expressions (e.g. "green holder IF colour = 'green'" or "round top IF model = 'round'").

Conclusion to the generic bill-of-material

Although, the objective of the generic BOM is to create a framework from which specific BOM's can be easily generated at customer order entry, it also a powerful method to describe the variety within a product family.

In relation to this research the major strength of the generic BOM concept is way it expresses causal links by coupling the generic BOM to parameter values, and in this way enables modelling the variety within a product family without requiring data redundancy.

Furthermore, the way the generic and specific items are arranged by van Veen & Wortmann [1987] in figure 5.7. represents some interesting visual aspects of modelling variety within a product family.

5.2.5. Product Family Master Plan

The product family master plan (PFMP) [Harlou, 2006] is a visual object oriented modelling approach. The PFMP enables a design team to make one united model for a whole product family. The basic idea behind the PFMP is to gather large quantities of information in a visual way on a poster in order to present an overview. The alternative is often to have the information in bills of material and technical drawings in a PDM system. Engineers tend to have their own drawings and spreadsheets stored locally on their computer or even in hard copy at their desk [Henderson, 1999].

The object oriented approach is somewhat similar to the principles used in the generic BOM as described above, and it makes it possible to gather the information of several product variants (i.e. the bills of material and drawings from people's desks) in one model without requiring large of redundant data. Therefore the PFMP is particularly suitable when the purpose is to get an overview of a series of products – one alternative being printing process involving all of all the different bills of materials of a potentially large number of products, which will be difficult to handle and navigate afterwards.

However, the PFMP has one major drawback when it comes to decision making about alignment. It is a product model and it only maps the variety in the product domain. There is no direct link to the production and supply chain. There is no visualisation of the state of variety/complexity at different levels in the value chain of a company and the supply chain in which the company fits.

The product family master plan (PFMP) is described further in section '6.3. PFMP', because it is a very important part of the framework for the descriptive study in this thesis. The reader is kindly asked to see Part 6 or the dissertation of Ulf Harlou [Harlou, 2006], should it be necessary. This section only has the purpose of briefly describe to what extend the PFMP tool satisfies the different requirements listed in Part 4.

Conclusion on the PFMP

The strength of the PFMP tool particular lie in the tools ability to model the variety and causal links in relation to the product structure and in this way describes how product features are realised physically by organs, parts, and assemblies and also describe how the physical parts and assemblies contribute and add value to the customer.

The major disadvantage of the PFMP tool is that it – although it takes different views (customer, engineering and part) – focuses on the products' structure alone without regards to other life phase system and neither the production or supply chain.

Furthermore, the PFMP method emphasise the power of visual communication and urges addition of illustrations, pictures, diagrams, etc. that can strengthen the message to be told. The relatively flexible modelling formalism used in the PFMP tool supports adding supplementary information in different formats to a greater extent than the matrices used in e.g. QFD, MFD, and DSM as described in the previous sections.

In this research the PFMP tool is used as the starting point for the developed support tool, primarily because of its ability to model commonality and variety within a product family, but also due to the methods visual capabilities.

5.2.6. Decision tree

The decision tree [Rea, 1965] is used by Tiihonen & Soininen [1997] as a product configuration model, which basically represents all the valid combinations of the components that can be used to obtain the desired functions for the customer. Figure 5.8. illustrates a visual representation of the decision tree (product configuration model).

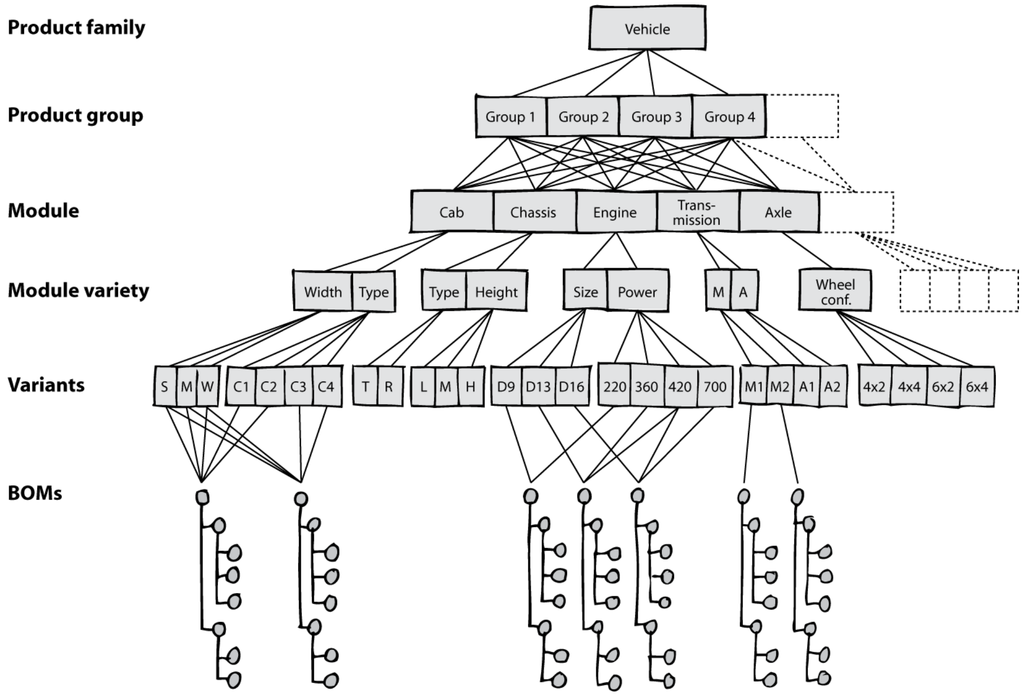

__Figure 5.8.__ The product configuration model, [Mesihovic & Malmqvist, 2004].

The decision tree presents the multitude of component variety within a product family and by the use of positive combinatory relationships (e.g. if "engine size"=D13 then "engine power" must be 360 or 420 hp) and/or incompatibility relations (e.g. if "engine size"=D13 then "engine power" cannot be 220 or 700 hp) it defines the possible product configurations.

Conclusion to the decision tree

In relation to this research work the decision tree provides a product configuration method that can be used to handle constraints within the products' structure, i.e. a way to describe combinatory rules.

Although, the model (as it is presented in figure 5.8.) has some visual strengths, the applicability of the visual representation is rather questionable if the number of product groups, modules, module variety, and variants is must higher in the depicted example.

5.2.7. Value Analysis

Value Analysis is a discipline founded at General Electric in the late 1940's [Fowler, 1990]. In short, value analysis is a methodology that has as its purpose to relate cost with functions in a product. It is a stepwise methodology in which a product is partitioned into smaller constituents for further analysis – that may be analysis of cost or value. Value is not the same as the Japanese idea of customer value we may see within the lean paradigm. Value is specifically defined as the "worth" relative to cost, i.e. value = worth/cost. Worth in this sense actually resembles the idea of customer value in lean very well. It is a denominator of those aspects, functions and features a customer wants to pay extra for. The customer is regarded as the downstream stakeholders in the supply chain. Worth is – in other words – a function of the totality of needs and demands of the customers, the customers' customers, the distribution channel etc. Some practitioners try to quantify worth and relate it directly to cost. Obviously cost is rather quantitative and measurable in hard currency, while "worth" is a more soft and qualitative size. Whether qualitative or quantitative, value has a focus on identifying value elements from a customer perspective and relate it directly to the functions of the product and thereby indirectly to the way the products are built.

Function Analysis System Technique – FAST

The Function Analysis System Technique (FAST) is a decomposition of a product into functions [Fowler, 1990], [Otto & Wood, 2001].

The basic idea is to make a functional model of the product based on so called functives. A functive is a two word sentence consisting of a verb and a noun, i.e. *functives = verb + noun*. Passive and indirect verbs like "supply" and "provide" that needs more than one additional noun to make sense is to be avoided, while more active verbs are preferable. Fowler gives an example in which a functive "provide cooling" can be made more active in the form "cool space".

In figure 5.9. below is an example of a FAST diagram. It is rotated for layout purposes.

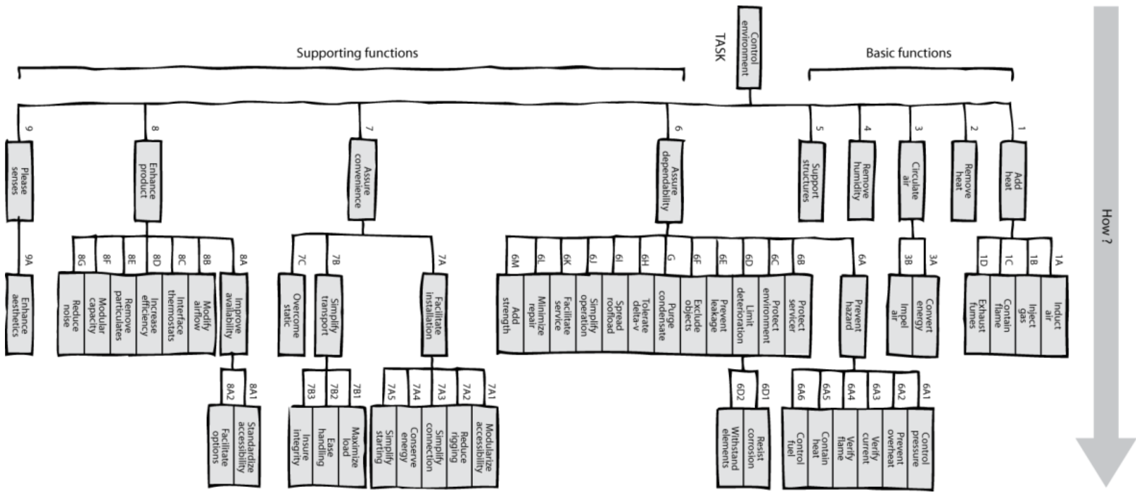

Figure 5.9. *A Function Analysis System Technique (FAST) diagram.*

Basic functions are the functions that are essential to the primary task, i.e. the main function of the product. Obviously this is a subjective question with an answer that depends on the product, the situation and the people involved in the analysis. Supporting functions are on the other hand not essential to the main function. They are more related to the differentiating features of a product, i.e. those features that differentiates a product from competing products. The supporting functions can be further sub-categorised into *required, aesthetic* and *unwanted* functions [Otto & Wood, 2001]. By successively expanding the diagram a team can form a total functional model of the product.

The FAST method resembles the functions means tree adopted from the Theory of Technical Systems [Hubka, 1973], yet the FAST approach does not explicitly map means but only functions (means are the physical bearers of functions – i.e. organs, as described in the Theory of Domains [Andreasen, 1980]). As with a function means tree the FAST diagram is used for single products and not a whole product family.

Conclusion to the value analysis

The gradual decomposition of the task function into basic and supporting functions in the FAST diagram, is an effective way to describe the functional structure of a product and to study how the functional features in a product are realised, i.e. what causal relations exist.

Distinguishing between basic and supporting functions - i.e. function that are critical and non-critical, respectively, to the overall functionality (task function) – is somewhat similar to distinguishing between value-adding and necessary variety (section '4.3.2. Value of variety') as supporting functions merely is a means to make basic functions work properly, and are needed as a consequence of the chosen basic functions. In this way the distinction between basic and supporting functions can help identifying what actually add value to the customer.

Unfortunately, the value analysis is not directly applicable on multiple product and/or product families.

5.2.8. Functional structures

The function-based design methods are characterized by the establishing either a function model [Pahl & Beitz, 1996], [Otto & Wood, 2001] or the schematics of the product [Ulrich & Eppinger, 1995]. The function structure describes the flow of material, data, and energy through sub-functions of the product using a set of rules (e.g. the rules that are referred to as the functional basis [Stone et al., 2000]), which basically is a common language to describe functional elements. The schematic of the product is somewhat similar to the function model. But where the function model describes the product using functional elements the schematics on the other hand can describe both functional and physical elements, whichever being the most meaningful (fig. 5.10.).

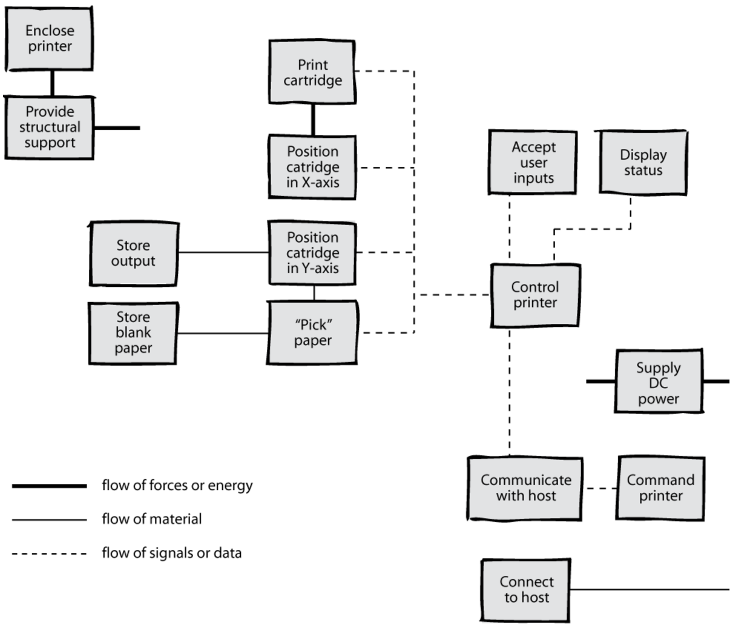

Figure 5.10. *The schematics of an inkjet printer. Note that some elements are functional whereas others represent the physical parts/assemblies.*

Having established an understanding of the functional structure of the product some methods base identification of modules on experience and some simple guidelines, i.e. a rather qualitative approach [Pahl & Beitz, 1996], [Otto & Wood, 2001], [Ulrich & Eppinger, 2000], [Pimmler & Eppinger, 1994]. Basically, these methods identify potential modules in a way similar to the way the MFD method makes use of the so-called module drivers. Ulrich and Eppinger [2000], for instance, consider the following factors as alternatives to the module drivers;

- Geometric integration and precision
- Function sharing
- Capabilities of vendors
- Similarity of design or production technology
- Localization of change
- Accommodating variety
- Enabling standardization
- Portability of the interfaces

Without going into further details it should be noted that there is a significant overlap between the above listed factors and the module drivers from the MFD method [Erixon, 1998], [Ericsson & Erixon, 1999].

Other design methods make use of more specific tools for identification of modules. One of the best described tools for identifying modules is the heuristic method which identify possible modules by examining the function model for different types of flow [Little et al., 1997], [Stone et al., 2000], [Otto & Wood, 2001], [Dahmus et al., 2001];

- *Dominant flow*
  The dominant flow heuristic examines each non-branching flow of material, energy or information through the function structure and groups the sub-functions the flow travels through until it is transformed into another flow or exits the system.
- *Branching flow*
  The branching flow heuristic examines flows associated with parallel function chains. Each parallel function chain defines a potential module. The module is formed of the sub-functions that make up the limb.
- *Conversion-transmission modules*
  The third heuristic method deals with so-called conversion and transmission sub-functions. Conversion sub-functions accept a flow of material or energy and convert the flow to another form of material or energy. If, additionally, a conversion sub-function exists in a chain with a transmit sub-function, then the chain presents an opportunity to form a module.

The use of the heuristics is like the function model based on the so-called functional basis.

Conclusion on the functional structures

The functional structure forms the basis for several different approaches to design or re-design of a product or a family of products. In general, the strength in these methods lies in the use of the functional view point on the product structure, i.e. functional structure.

Considering different factors in order to determine advantages of clustering, i.e. modules, indicates awareness about life phase system relations. Combined, this rather qualitative approach and the more systematic identification of potential modules using the so-called heuristics, forms a powerful tool for generating modular architectures.

In relation to this research the major drawbacks of the methods are the lack of supply chain considerations, and the fact that the modelling method doesn't support modelling of product variety.

5.2.9. Multi-criteria assessment

Otto and Hölttä-Otto [2007], [Otto & Hölttä, 2004] presents a technique based on multi-criteria assessment where platform concepts are given a score based on a set of different weighted criteria. Although, the method is designed to be used for screening of preliminary platform concepts, and not - as it is the focus of this research - analysis and re-design of product families, the method include analysis aspects that should be considered.

Figure 5.11. illustrates how 19 metrics grouped under 6 categories are used to evaluate different aspects of a platform concepts performance capabilities.

The method is based on relatively quantitative metric adapted from the field of modularity, platform design, and product development in general (e.g. functional structure, DSM, commonality indices, etc.).

Overall multi-criteria platform assessment				Score 8.0	Grade B - good
	Marginal corporate focus	Percentage corporate focus	Weighted contribution	Score	Grade
Platform scorecard					
Portfolio customer satisfaction	9	35	2.5	7.2	B - good
Product variety	9	35	2.9	8.4	B - good
After sale support	3	12	1.0	8.9	B - good
Organizational alignment	3	12	0.8	6.7	C - acceptable
Upgrade flexibility	1	4	0.4	9.6	A - outstanding
Development complexity	1	4	0.3	7.2	B - good
		100	Total	7.9	B - good
Portfolio customer satisfaction scorecard					
Cost-worth distribution	9	50	4.0	8.0	B - good
Portfolio customer needs	9	50	3.2	6.3	C- acceptable
	9	100	Total	7.2	B - good
Product variety scorecard					
Planned upgrade carryover	9	33	3.1	9.4	A - outstanding
Common modules	9	33	2.0	5.9	C - acceptable
Specification variety	9	33	3.3	10.0	A - outstanding
	9	100	Total	8.4	B - good
After sale support scorecard					
Partitioning for reliability	3	33	2.9	8.6	B - good
Partitioning for service	3	33	3.3	10.0	A - outstanding
Environmental friendliness	3	33	2.7	8.1	B - good
	3	100	Total	8.9	B - good
Organizational alignment scorecard					
Ease of assembly	3	25	1.7	6.9	C - acceptable
Aligned with the organization	3	25	1.3	5.4	C - acceptable
Make-buy	3	25	2.3	9.2	A - outstanding
Testability	3	25	1.4	5.4	C - acceptable
	3	100	Total	6.7	C - acceptable
Upgrade flexibility scorecard					
Unknown isolation	1	50	5.0	10.0	A - outstanding
Change flexibility	1	50	4.6	9.1	A - outstanding
	1	100	Total	9.6	A - outstanding
Development complexity scorecard					
Function and form alignment	1	20	1.9	9.7	A - outstanding
Interface flexibility	1	20	2.0	10.0	A - outstanding
Anti-synergy avoidance	1	20	0.0	0.0	F - unacceptable
1 DOF adjustments	1	20	2.0	10.0	A - outstanding
Limited extremes	1	20	1.3	6.6	C - acceptable
	1	100	Total	7.2	B - good

Figure 5.11. *The multi-criteria assessment platform scorecard. 19 metrics – divided in 6 categories – are used to evaluate preliminary platform concepts.*

I will not explain in further detail all 19 metrics but merely elaborate on the 6 categories as they describe the aspects of method sufficiently;

- *Portfolio customer satisfaction*
  The method acknowledges the importance of meeting the customer needs by assigning relatively high weight for the two metrics. The reason for using two metrics is to distinguish between value distribution in a single product (cost-worth distribution) and the value of variety (portfolio customer needs).
- *Product variety*
  This category determines the platform concepts ability to generate product variety by reusing modules across product variants and/or product generations and also by encapsulating specification functions in isolated modules.
- *After sales support*
  This category includes metrics that describe how well the product's after launch life has been taken into account. That is, metrics for reliability, service and environmental friendliness, i.e. do the modular platform support these life phase aspects?
- *Organizational alignment*
  The organizational alignment category touches upon the very important aspect of how well the product design fits into the supply chain and vice versa. The category includes aspects of assembly, organisational alignment, outsourcing, and testability.

- *Upgrade flexibility*
  The two metrics in this category describe how flexible the platform concept is and how easily it can adapt to changes in customer demands, technology evolution, etc.
- *Development complexity*
  The final category includes metrics that evaluate the complexity within the products' design as seen from various viewpoints.

Conclusion on multi-criteria assessment

Although, the method is not planned to be used for analysis of already launched product families, the multi-criteria assessment method touches aspects of a product family's general performance that are relevant to consider also in relation to re-design of such a product family.

The method has is primary advantage in the broadness of the metrics that are considered.

The fact that the method is based on a mixture of rather qualitative and quantitative metrics, respectively, is also considered to be one of the major strengths of the method.

On the other hand the format of the tool conceals what causes the result, meaning that if you haven't been part of the assessment all you get is a number, which tell you if the concept is good or bad. As such the method doesn't facilitate discussions that have the purpose of resolving contingent design issues. Rather the method gives a rather shallow indication of where to look for what causes an undesirable score.

5.2.10. Measuring performance of product families

Meyer & Lehnerd [1997] presents in relation to platform-based product development a 6 step method to analyse performance from a product family perspective;

1. *Gathering the necessary data*
   The data required for the following analysis include: engineering costs, development time, manufacturing costs, market development costs, sales data and margins.
2. *Understanding the efficiency of platforms for creating derivative products*
   The measure for platform efficiency is used to see how performance has improved or declined over a period of time with regards to engineering costs that are needed to develop derivative products. The platform efficiency is defined as the ratio between the derivative product engineering costs and the platform engineering cost.
3. *Understanding the time to market consequences of platform development*
   Similar to the platform efficiency measure a measure for cycle time efficiency is used to elaborate on the performance regarding development time for derivative products. The cycle time efficiency is defined as the ratio between the elapsed time to develop a derivative product and the product platform, respectively.
4. *Understanding the technological competitive responsiveness of the firm*
   The launches of key product innovations are mapped relative to the company's main competitor's launch of similar product innovation in order to analyse the company's lead-lag competitive responsiveness, i.e. to analyse the performance regarding time to market.
5. *Understanding the commercial effectiveness of platforms*
   The platform effectiveness is basically and expression for the revenue provided by the platform, and is defined as the net sales of derivative products compared to the development costs of each derivative product plus the platform development costs.
6. *Understanding profit potential*
   The final measure targets the profitability of the derivative products. The cost price ratio (CPR) is calculated as the cost of goods (material, labour, fixed and variable overhead) divided by the net sales.

Conclusion to measuring performance of product families

First of all, the method is primarily a tool that can be used to justify involvement in platform-based product development and the investments that is needed to develop such a platform. That is, measuring performance of product families that are based on product platforms. All measures assume that resources have been spent on developing a platform. Consequently, the measures (and the method as such) cannot be used to assess performance of product families that are not based on product platform.

Furthermore, the measures presented by Meyer & Lehnerd [1997] are calculated from data, which necessarily must be derived from a relatively long period of time, and of such a high level that it is difficult to directly link the results to presence of a product platform, as many others factors could have influenced the engineering costs, development time, market development costs, etc.

In relation to this research the method only contributes to a very limited extend as to get an understanding of what aspects should be considered when assessing product families.

5.2.11. Rationalising product lines

Andersons & Pine [1998] present a technique to rationalise product lines before implementing just-in-time, build-to-order, flexible manufacturing, etc. By rationalising the product line the authors mean eliminating out-dated and less profitable products that should not distort a future mass customization setup.

The technique considers the following 12 rationalisation criteria whereof the 5 first are quantitative and there rest qualitative;

1. *Sales volume*
   The sales volume of all products are analysed using a Pareto sort format plot. The product variants sold in the highest volume have a higher probability of avoiding to be discontinued.
2. *Sales revenue*
   Similarly, the sales revenue of all products can be sorted in a Pareto plot and analysed.
3. *Part commonality*
   One approach to analyse the part commonality, is to make a list of commonality or "preferred" parts (contrary to unique and unusual parts) and plot the products according to percentage of common parts in a Pareto sort.
4. *Cost of variety*
   The technique includes a method to calculate the cost of variety for each product under consideration. The calculation model includes costs related to inventory, production setup and changeover, materials, operations, customization/configuration, marketing, quality, service and flexibility. Again, the cost of variety is analysed in a Pareto plot.
5. *True profitability*
   Calculating the true profitability is somewhat a challenge. Activity-based cost management (ABC) [Bukh & Israelsen, 2004] can provide a realistic indication of profitability. Again, products having the highest profitability have a higher probability of remaining in the assortment.
6. *Polls and surveys*
   Polls and surveys is presented as an alternative or supplement to calculating the true profitability of the products. Typically, factory workers, production planners, product managers, dealers, sales people, etc. have an opinion of what products are profitable or not. The idea here is to query these people for their opinions and/or experiences (e.g. what products do often cause problems, etc.).
7. *Factory processing*
   This step is particular concerned with identification of product variants that does not fit very well into a flexible manufacturing environment. The technique presents a list to especially sceptical of when analysing the products (e.g. older products or products acquired mergers and acquisitions).

8. *Functionality*
   This step looks for opportunities to consolidate products that have similar (overlapping) functionality. For instance, if an old product is not discontinued and still competes with the new slightly improved replacement product.
9. *Customer needs*
   This step states the importance of analysing the variety in the product family from a customer view point.
10. *Company core competencies*
   Products representing the company's core competencies with regards to technology, processing, product development, marketing, etc. should have a greater chance of staying in the assortment.
11. *Clean-sheet-of-paper scenario*
   A strong tool to prioritise the products is to role-play the scenario pretending to be a well-financed new competitor, i.e. what products would you have if you could start on a clean sheet of paper?
12. *Future potential*
   The existing products are evaluated and prioritised subjectively according to their presumed future potential including aspects of technology, markets, demographics, corporate strategy, etc.

Conclusion to rationalising product lines

The rationalisation technique presented above has its absolute strength in the broadness of aspects that are covered in the 12 steps.

In relation to this research the technique provides a method prioritise the products according to their strategic importance to the business using quantitative as well as qualitative analyses.

Furthermore, the technique includes experience from factory workers, production planners, product managers, dealers, sales people, etc. in the evaluation of the products. In this way contingent critical design issues are captured and can possibly be eliminated.

Besides the Pareto plots used to present the quantitative information the method does not provide any readily applicable tools, but merely presents a list of aspect that should be considered when rationalising a product line, and as such it somewhat an exaggeration to term the list as a technique. This is considered to be a major disadvantage of the method.

5.2.12. Evaluation indices

There has been made extensive research on using indices (i.e. metrics) for evaluating different aspects of product families. Generally, all these methods base the evaluation of the product family solely on the physical structure of the products. That is, the indices basically focus on a comparison of the physical components and coherent interfaces within the product variants in a product family.

As the number of different indices are endless and the difference between are somewhat negligible I will not describe these indices in detail but merely list a few and comment upon what they indicate.

- *Degree of commonality index (DCI)*
  The degree of commonality index (DCI) is used to assess the commonality between the components in a number of product variants. This type of index is the one that gets the most attention in the research literature and many similar indices (with distinct names) have been developed since [Collier, 1981].
- *Total constant commonality index (TCCI)*
  Similar to the degree of commonality index [Wacker & Trelevan, 1986].
- *Commonality index (CI)*
  Similar to the degree of commonality index [Martin & Ishii, 1996 & 1997].
- *Component part commonality index ($CI^{(C)}$)*
  Similar to the degree of commonality index [Jiao & Tseng, 2000].

- *Percent commonality (%C)*
  Similar to the degree of commonality index [Siddique et al. , 1998].
- *Comprehensive metric for commonality (CMC)*
  Similar to the degree of commonality index [Thevenot et al., 2007].
- *Coupling index (CI)*
  The coupling index (CI) is used to indicate how coupled the components in a product is, i.e. if one changes are made to one component how likely is it that this entails changing adjacent components [Martin & Ishii, 2007].
- *Generational variety index (GVI)*
  The generational variety index (GVI) is index is a number that indicates what elements in a product that is most likely to change over time, i.e. from one product generation to the next [Martin & Ishii, 2007].
- *Commonality diversity index (CDI)*
  The commonality diversity index indicates the difference between the existing and the ideal trade-off, which is defined as follows: (a) common functionality should use common components, (b) unique functions should use unique components, and (c) variant functions should use variant components [Thevenot et al., 2007].
- *Differentiation point index (DI)*
  The differentiation point index is used to indicate how much variety a process needs to handle compared to the number of processes and the number of final product variants offered [Martin Ishii, 1996].

A more comprehensive description and evaluation of the various evaluation indices was made by Thevenot and Simpson [2004].

Conclusion on evaluation indices

Though, the evaluation indices can be used to tell for instance how similar and/or different products seen from a strictly physical component-based viewpoint the applicability of such indices is questionable. As it is discussed in section '3.3.1. Variety and commonality' commonality is a property, which can only be observed in relation to the product's meeting with other life phase systems.

The perception that the degree of commonality can be derive directly from the structure of the physical products to some extend suggest a one-to-one trade-off between variety and commonality, and that it is not possible to co-optimise the two as discussed in section '3.3.1.Variety and commonality'.

5.2.13. Platform-based product family design

Gonzales-Zugasti et al. [2000] offers a general method for architecting product platforms based on the study of common features in the existing product portfolio which should form the basis of the product platform. As a part of the platform design process a set of product variants similar to initial products which were used to identify the platform are then derived from the platform. The new generation of product variants are compared to the initial products and the platform basis is evaluated, renegotiated and if necessary redesigned (fig. 5.12.).

Conclusion on the platform-based product family design

The model in figure 5.12. presents a rather useful suggestion to what steps should be included in the process of re-designing a product family, as this research work focus on redesigning product families and finding more efficient way to derive the needed product variants. Unfortunately the work does not present any readily applicable tool to be used in of the steps.

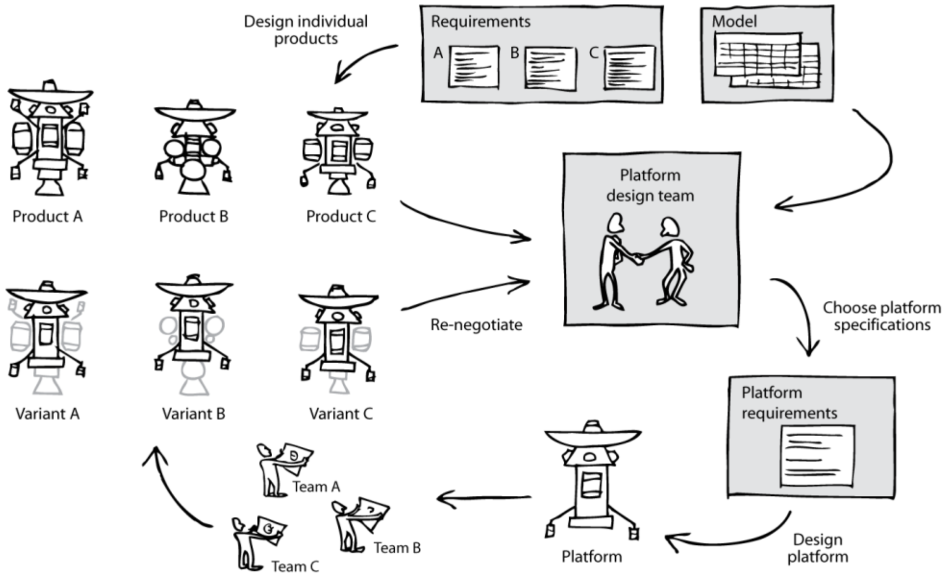

Figure 5.12. *A platform-based product family design implementation approach.*

5.2.14. Value stream mapping

Most value stream mapping tools has a focus on information and physical goods passing through the supply chain. The value stream is consequently often perceived as the flow of materials through the value adding processes. There are several value stream mapping tools [Hines & Rich, 1997], [Womack & Jones, 2003], [Christiansen et al., 2006], [Liker, 2004], [Rother & Shook, 2003], [Rother & Harris, 2001]. This section describes the "traditional" value stream mapping tool. Other tools or methods re describe in the subsequent sections.

Icon	Icon name	Description
	Process box	Describes an activity in the value stream. Includes a title and description of the process, as well as data, like process time, setup time, and so on.
	Outside source	Indicates and indentifies both customers and suppliers.
	Truck	Indicates an outside delivery - either to a customer or from a supplier.
	Information	Describes information transmitted along the value stream.
	Electronic information transmission	Indicates that the information is transmitted electronically.
	Manual information transmission	Indicates that the information is transmitted manually.
	Inventory	Identifies stored inventory - either raw materials, in process, or finished goods.

Icon	Icon name	Description
	Finished goods movement	Indicates when materials in a finished state are moved along the value stream. This can be a supplier moving its product to a company or a company moving its product to its customer.
	Material push	Indicates material being pushed through the process. The push is usually a production plan or schedule.
	Supermarket	Indicates in-process inventory stored in a controlled environment called a supermarket.
	Material pull	Indicates amterial movement via a pull signal (kanban).
	Operator	Indicates that one or more operators are present at a process step.
	Kaizen burst	Indicates the need for and description of a *Kaizen* activity within the value stream.

Figure 5.13. *Value stream mapping icons. The "Kaizen burst" refers to situation in which an improvement activity is needed. [Sayer & Williams, 2007].*

A value stream map in its traditional form is a process activity map. It is a visual drawing depicting a certain part of the supply chain, with aspects such as the flow of materials and information, the different working stations, in which the processes happen, inventories where the items are on stock, and transportation types and routes. The most common value stream map includes information and materials, i.e. the last two of the above three basic elements of the value stream definition [Rother & Shook, 2003]. However, the methodology described below is also utilised in lean product development projects, in which a product concept is the modelling object.

This rather standardised way of doing value stream mapping offers a set of very useful icons to choose from when drawing the flow (fig. 5.13.). They also give a quick overview of the elements that are modelled in a value stream map.

Usually, a value stream map is used to visualise the activities in a supply chain. In a lean change process a *current state* and *future state* map is drawn.

Current state

The current state describes the as-is situation with a special emphasis on highlighting the non value adding processes related to a specific product. The purpose of the map is to support the search for waste. In this case – as there is a natural focus on process efficiency – the value stream will reveal the seven original waste types described in section '3.4.2. The concept of waste' (overproduction, waiting, transport, inappropriate processing, unnecessary inventory, unnecessary motion and defects). Waiting, transport, motion and inventory become particularly visible as they are drawn directly on the map, while the other may have to be interpreted by the users of the map. Figure 5.14. below shows a typical example of a current state map.

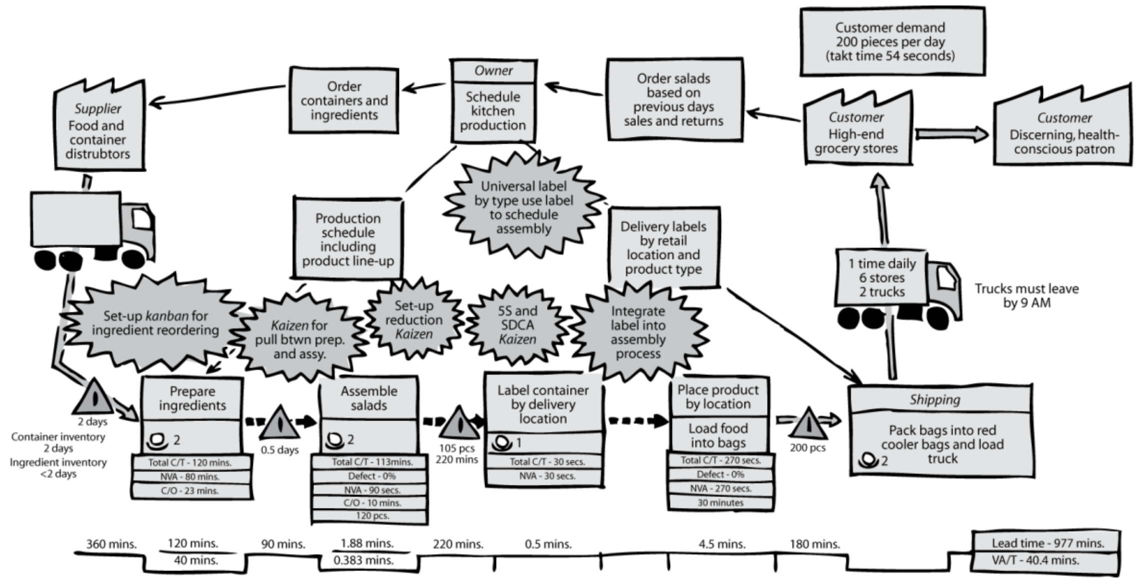

Figure 5.14. *A current state value stream map. The timeline below gives an impression of bottlenecks and actual time spent in operations, [Sayer & Williams, 2007].*

Future state

The future state describes the ideal future setup in which the non value adding activities are eliminated. The future state is used as a scenario for a future setup and as such a conceptual sketch to work further on. The graphics and symbols are similar to those of the current state map even though the contents usually describe a more efficient flow. The future state version of the value stream map is illustrated in figure 5.15.

Jones & Womack [2003] also introduced the *extended* value stream map, which is intended to include the entire supply chain instead of only a single tier up- and downstream. Consequently, the extended value stream map includes a few additional icons.

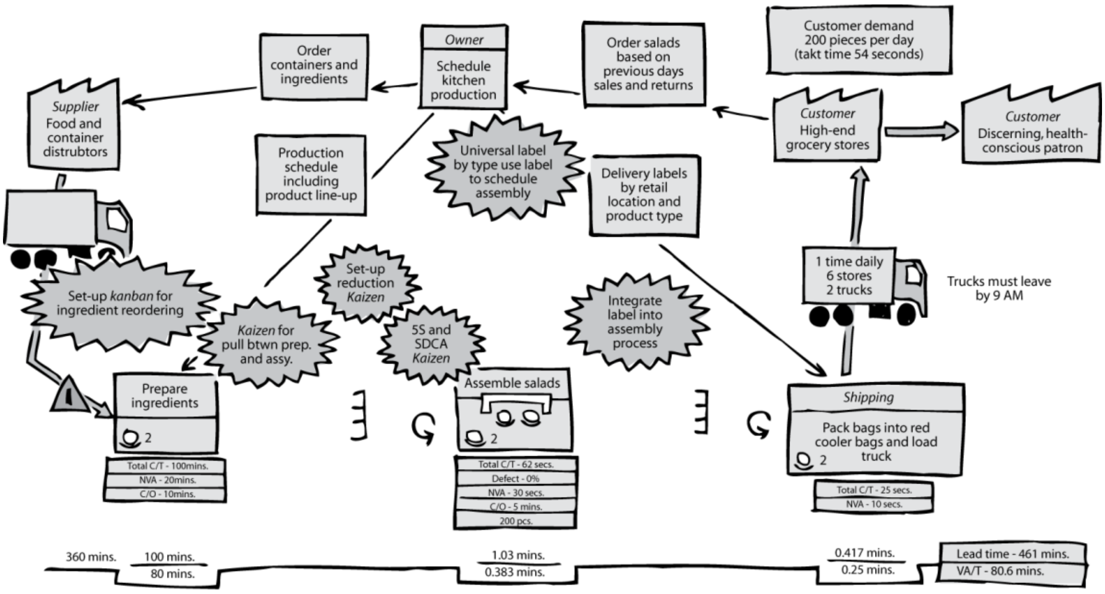

Figure 5.15. *A future state value stream map, [Sayer & Williams, 2007].*

Conclusion on the value stream map

The value stream map (VSM) has its focus on optimising the flow of materials and information, and is as such a very powerful tool to identify waste. The VSM purely include production aspects in the analysis, and is in no way concerned with the design of the products and life phase system relations in that aspect.

The prime strength of the VSM is the tool's visual capabilities which are derived by the use of relatively simple symbols to model the flow.

The major weakness of the VSM in relation to this research is the shortage of aspects related to the products' design, as it is a tool that originates from the lean production paradigm.

5.2.15. Deployment flowchart

A deployment flowchart maps the process steps in the supply chain similar to the VSM method above. Furthermore, the deployment flowchart links the flow of information and materials to the organisational structure of a company [Scholtes, 1998] (fig. 5.16.).

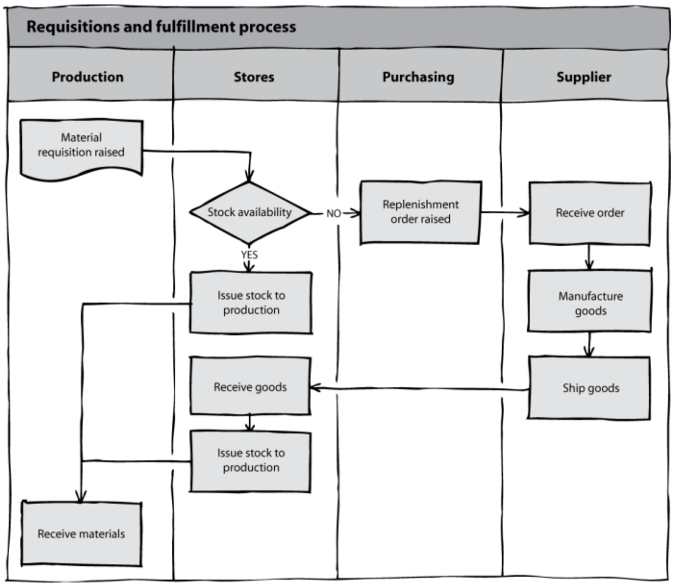

Figure 5.16. *An example of a deployment flowchart.*

In relation to this research the deployment flowchart can - when constructed correctly - be used to acquire a good understanding of the value creation process and reveal duplication, unnecessary, and/or undesirable steps in the process.

Conclusion on the deployment flowchart

As mentioned the main contribution of the deployment flowchart compared to other process mapping tools is the methods ability to link the steps to the functional organisation of the company in a very simple and visual way.

The method dedicates full attention to analysing and optimising the flow of information and materials through the supply chain without any consideration of aligning it to the product design or the opposite.

5.2.16. Process activity mapping

A less graphical depiction of the value stream is a process activity map [Hines & Rich, 1997]. It is a schematic representation of the critical path of a production. It is basically a matrix containing a mapping between process steps and machines, time consumption and distance along with other factors of choice (fig. 5.17.). This tool may be used in conjunction with the traditional value stream map or as a preparation of that.

#	Step	Flow	Machine	Distance (m)	Time (min)	People	Operation	Transport	Inspect	Store	Delay	Comments
1	Raw material	S	Reservoir				O	T	I	S	D	Reservoir/ additives
2	Kitting	O	Warehouse	10	5	1	O	T	I	S	D	
3	Delivery to lift	T		120		1	O	T	I	S	D	
4	Offload from lift	T			0.5	1/2	O	T	I	S	D	
5	Wait for mix	D	Mix area		20		O	T	I	S	D	
6	Put in cradle	T		20	2	1/2	O	T	I	S	D	
7	Pierce/pour	O	Mix area 12		0.5	1	O	T	I	S	D	
8	Mix (blowers)	O			20	1/2	O	T	I	S	D	Base material, blow & additives
9	Test #1	I			30	1+1	O	T	I	S	D	Sample test
10	Pump to storage tank	T	Store tank	100		1	O	T	I	S	D	Dedicated reservoir
11	Mix in storage tank	O	Store tank		10	1	O	T	I	S	D	
12	J. R. rest	I			10	1+1	O	T	I	S	D	Stamp & approve
13	Await filling	D			15		O	T	I	S	D	Longer if screen late
14	To filler head	T		20	0.1	1	O	T	I	S	D	
15	Fill/top/tighten	O	Filler head		1	1+1	O	T	I	S	D	1 unit
16	Stack	T	Pallet	3	0.1	1	O	T	I	S	D	1 unit
17	Delay to fill pallet	D			30		O	T	I	S	D	
18	Strap pallet	O			2	1	O	T	I	S	D	
19	Transfer to storage	T		80	2	1	O	T	I	S	D	
20	Await truck	D	Store		540		O	T	I	S	D	Batch 360/ queue 180
21	Pic/move by fork lift	T		90	3	1	O	T	I	S	D	Fork lift
22	Wait to fill full load	D	Lorry		30	1+1	O	T	I	S	D	1 operator, 1 haulier
23	Await shipment	D	Lorry		60	1	O	T	I	S	D	1 haulier
	Total		**23 steps**	**443**	**781.2**	**25**	**6**	**8**	**2**	**1**	**6**	
	Operators				**38.5**	**8**						
	% value adding				**4.93%**	**32%**						

Figure 5.17. *A process activity map. Note the way different types of operation is shown [Hines & Rich, 1997].*

First the processes are listed and the flow between them is considered. Then waste is identified as those activities that are not value adding. On the basis of that analysis one may come up with alternative routings and sequences in order to improve efficiency where it is possible, along with new flow patterns and a critical consideration of the necessity of all tasks.

The so-called *5W1H* method prompts the questions Why, Who, Which, Where, When and How. It gives a simple yet structures approach to identify waste in a value stream. Why does an activity, task or process occur, who runs it and who is in charge, on which machine and where does it happen? When and how? Such questions are typical and will drive the persons in charge of a value stream mapping process through a conscious evaluation of all of the activities in the value stream, making way for an identification and elimination of waste.

The 5W1H method is also useful after having made a traditional value stream map, as described in the former section.

Conclusion on the process activity map

The process activity map is basically a VSM without the visual representation. Compared to the VSM the only strength of the process activity map is its capability to handle a large amount of information, unfortunately, on the expense of the visual overview.

Furthermore, the process activity map is alone concerned with the flow of materials and does not incorporate the flow of information as the VSM does.

Again, the process activity only includes aspects related to the production and the supply chain.

5.2.17. Paper Kaizen

Paper Kaizen [Rother & Harris, 2001] is a method closely related to the process activity mapping. It is an improvement method used to optimise details in a process, such as an operator waiting for a machine to stop 5 minutes every hour instead reversing to tasks and doing value adding activities another place in the factory. Paper Kaizen may help reveal such small and hidden amounts of waste. Paper Kaizen is simply made by following an operator or part/assembly and listing all activities along a time scale. One may then draw an improved future state version of that activity next to the current state in the search for potential (fig. 5.18.).

Conclusion on the paper kaizen

The objective of using the paper kaizen method is optimising a sequence of activities by eliminating small sources of waste. As the method relies on tracking a person or part it is more suitable for analysing and optimising of a relatively isolated sequence activities that happens over a relatively short period of time, as for instance an assembly sequence as the one in figure 5.18. In paper kaizen it is the sum of adjusted details that make up the results, i.e. shortening the process time a couple of seconds here and there by making incremental changes to the working procedure.

In relation to this research the paper kaizen method especially the visual representation is interesting as it illustrates very where in the sequence of activities lies the greatest improvement potential.

As goes for the other value stream modelling tools, the paper kaizen method doesn’t either include aspects related to the structure and design of the product, nor does it include any aspects of variety (process or product).

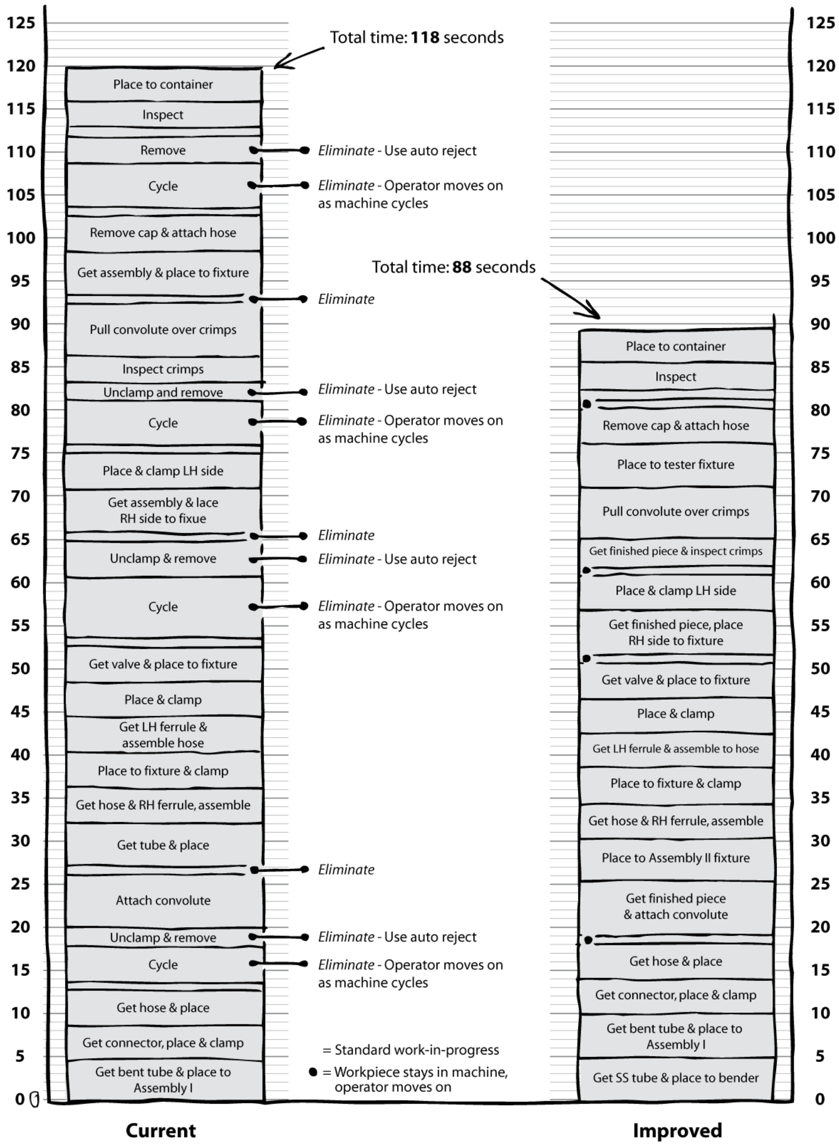

Figure 5.18. *An example of a Paper Kaizen, showing a current and future state process sequence [Rother & Harris, 2001].*

5.2.18. Production variety funnel

Another visual way to represent a value stream is a production variety funnel. It is a rather sketchy modelling technique with little detail but it visualises an important point. There are several points of variegation in a supply chain and the variation gradually grows throughout the chain. The point of variegation is introduced in section '4.3.6. Point of variegation' as the point at which variety is introduced to the supply chain, resulting in a rise in the number of semi-manufactures, parts, assemblies, finished goods, etc. As it was discussed, there is not a single point of variegation rather the complexity gradually expands (or declines) at various points throughout the supply chain. The complexity may decline if a large number of raw materials are processed and assembled into a relatively limited number of different finished goods. New [1974] has formulated four types of factories representing different complexity patterns. The letters denote the shape of the production variety funnel, if you imagine the flow going from bottom to top.

- ***T** factory:*
  The T factory is a factory with relatively limited variety in incoming raw materials. At a certain point, typically the final assembly, a multitude of different variants are made, resulting in great variety towards the customers. The ideal Mass Customization factory is a typical T factory.

- ***I** factory:*
  The I factory has roughly the same complexity throughout the whole supply chain. Some processing industries or simple mechanical products are characterised by a simple raw material input and a relatively simple output.
- ***V** factory:*
  The V factory has one or few raw materials as input and the complexity gradually grows throughout the factory while ending up with a fairly complex output. Figure 5.19. shows a typical V factory.
- ***A** factory:*
  The A factory is a somewhat opposite to the V factory. A complex raw material input is made into one or few different products.

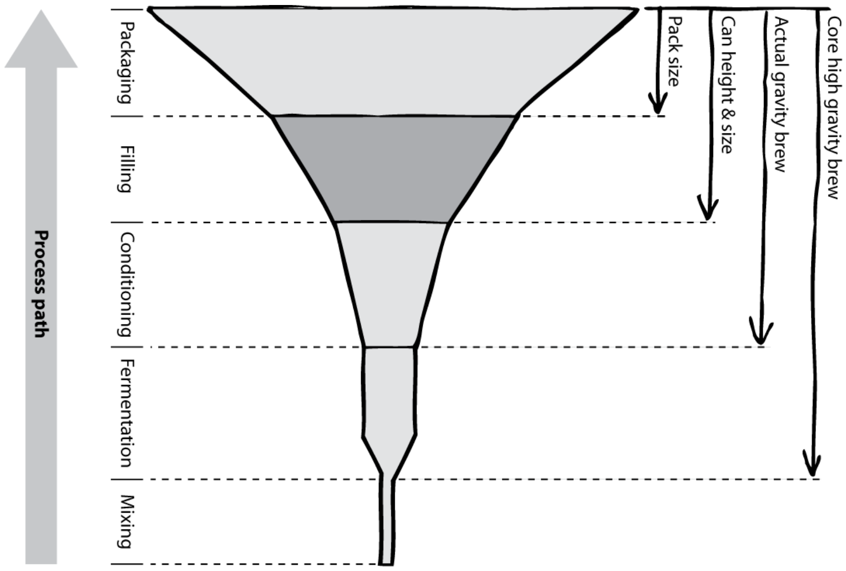

Figure 5.19. *A V shaped production variety funnel. A simple mix of ingredients is gradually expanding in complexity as an increasing number of customer specific characteristics are added [New, 1974].*

It is of general interest for managers to be aware of the type of factory that they operate. A mechanical manufacturing plant with a typical V shape can be turned into a more flexible T setup using Mass Customization, Postponement and modularisation principles. Looking for waste and improvement potential is also a task of looking at the right distribution of complexity in the supply chain. The production variety funnel is a tool that supports these production schemes.

Conclusion on the product variety funnel

The primary strength of the product variety funnel is the methods ability to visualise the development of variety and the concomitant complexity through different steps in the supply chain, and hereby indicate the potential of postponing the point of variegation.

The major drawback of the method is the lack of details. That is, details about the product structure as well as the supply chain. The product variety funnel analyses the variety at such a high level that details which explains the source of or reason the expansion or contraction of variety are not identified. Consequently, the method cannot directly be used to generate ideas for changes in product design and/or the supply chain in order to postpone the point of variegation. Instead, the product variety funnel can be used to express the potential benefit of postponing the point of variegation seen from a more general point of view.

5.2.19. Quality Filter Mapping

A quality filter map is a graphical view of the quality throughout the supply chain. Three quality aspects are considered to be within quality filter mapping;

- Product quality
- Defect quality
- Service quality

These types of quality are then quantified and drawn at different levels within the company or on a broader scale within a section of the supplier chain – e.g. one or two tier levels up- and downstream from the company of scope.

An example quality filter map is shown below in figure 5.20.

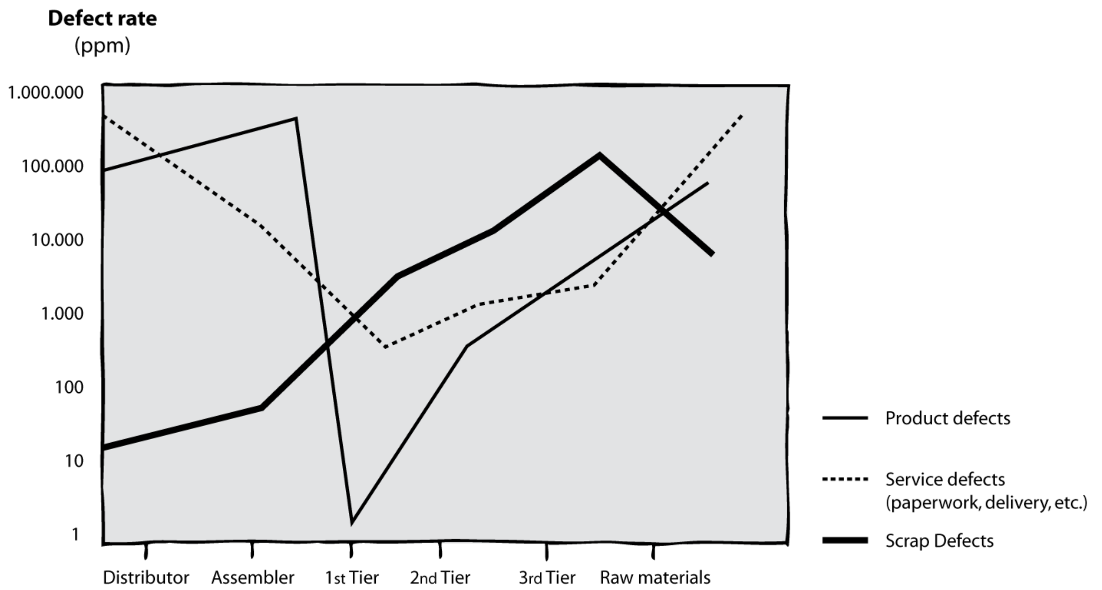

Figure 5.20. *A quality filter map showing the defect rate in parts per million in the distributor level and as far back as the third Tier and raw material suppliers [Hines & Rich, 1997].*

The example gives an impression of the possible waste improvements that might be possible to harvest in the supply chain.

Conclusion to the quality filter mapping

As the quality filter map illustrate the defect rate level at a number of tier levels up- and/or downstream in the supply chain it can be used to locate at what tier level critical design issues can be found.

Due to lack of details included the method cannot be used identify the actual design issue causing the less than satisfactory defect rate at a given tier level. That is why the quality filter map in relation to this research primarily is relevant because it indicates the potential of resolve any contingent design issues that cause a higher defect rate.

5.3. Conclusion

The review of existing methods and models reveal a multitude of different visualisation approaches and models for assessment of product design and flow in operations in relation to product families and single products.

Figure 5.21. present an overview of how well the evaluated methods and models meet the requirement established in section '4.3. Requirements' using a 5 step scale stretching from "not meeting the requirement at all" to "fully meets the requirement".

From figure 5.21. it is clear no single method or model meets all the identified requirements. The methods can generally be divided into two groups: (a) methods that are relatively visual but only focus on aspects related to a single or few requirements and (b) methods that have a broad focus and touch many aspects but lack visual qualities. Furthermore, the former group of methods are typically based on detailed data or knowledge affiliated to either the product development or the production paradigm.

In the following descriptive work it decided to take a starting point in the PFMP tool. Figure 5.21. indicates that the PFMP tool has some shortcomings – especially aspects concerning the supply chain and life phase system relations needs attention in the descriptive work.

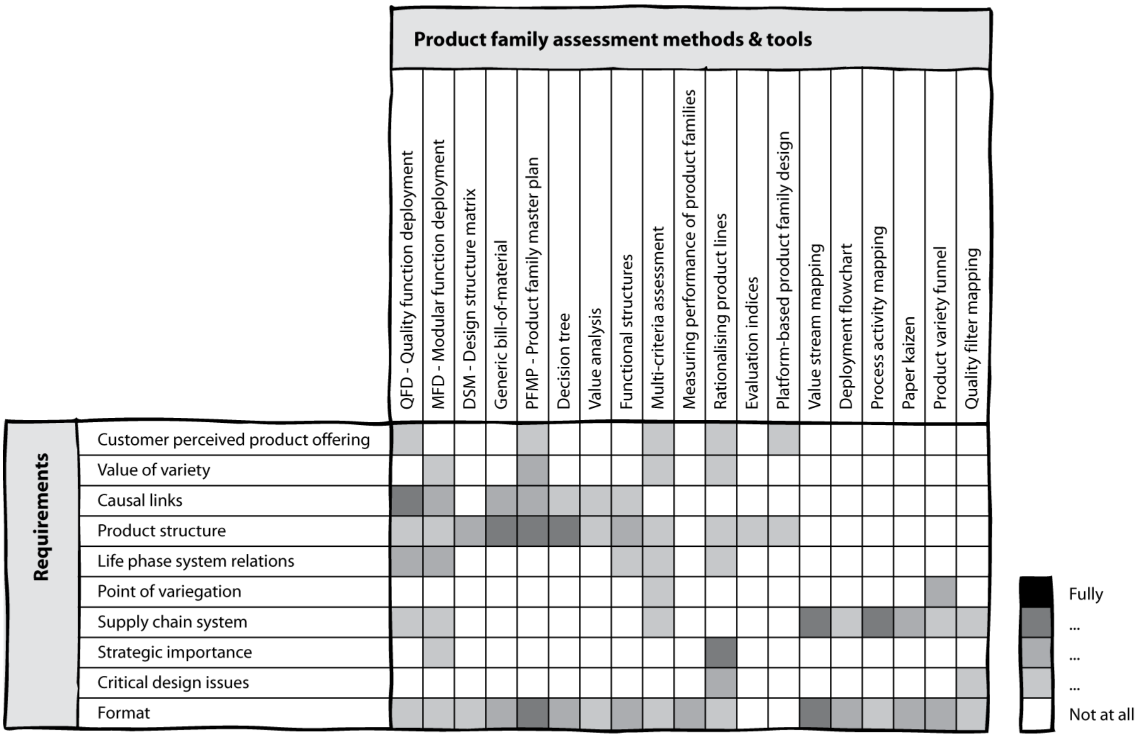

Figure 5.21. *Overview of how well the presented product family assessment methods meet the requirements that where established in the section ' Requirements'.*

Part 6

PFMP² – the Extended Product Family Master Plan

Part 6 introduces the developed modelling formalism that can support decision-making in the process of re-designing the products in a product family with a view to make production of the needed product variety more efficient/effective. The tool is an extension of the existing the PFMP tool – a tool for modelling product families from and especially variety of product families. Thus, the tool is denoted PFMP².
The PFMP² tool aims at modelling product families from additional viewpoints and link these views to each other and hereby render visibility of relation between the products' design and relevant product life systems – especially systems related to production and the supply chain in general.

6.1. Introduction

This research has its starting point in the PFMP tool presented by Harlou [2006], and the result is intended to be an extended version of this tool. Accordingly, the support tool developed as a result of this research work is denoted *PFMP² – the extended product family master plan*.

The PFMP² tool has the objective of fulfilling the requirements that has been formulated in part 4 as a result of a descriptive study, with emphasis on modelling product families from different viewpoints and linking these viewpoints in order to acquire an understanding of relations between the products' design and different life phase systems.

This section has the purpose of demonstrating the PFMP² modelling formalism using a family of bicycles as recurring example and explains how the requirements are meet by the tool.

6.2. The PFMP² modelling formalism

As illustrated in figure 6.1. the PFMP² tool is composed by 4 different modelling elements.

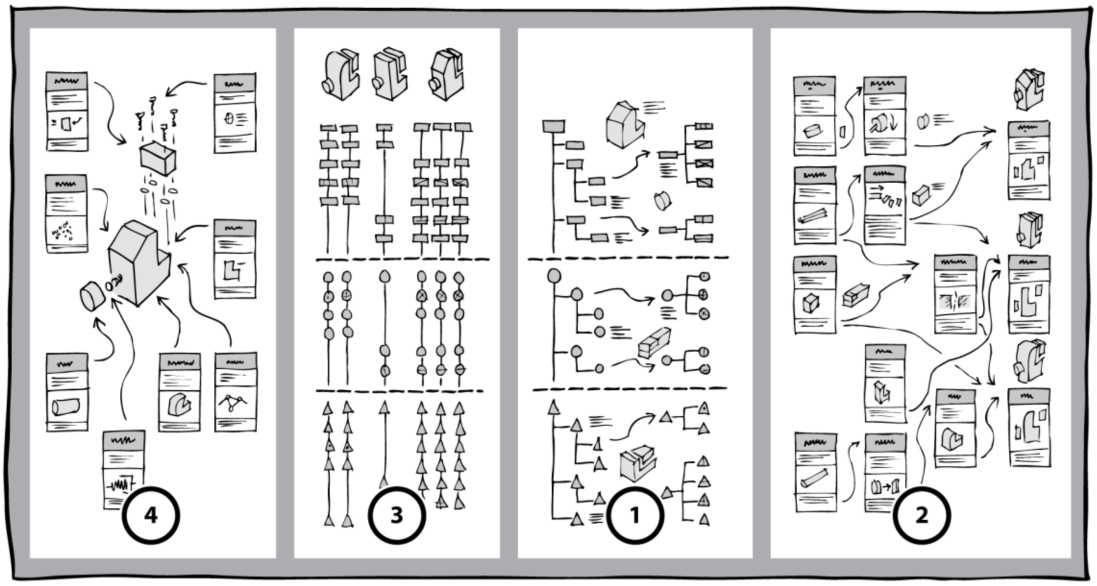

Figure 6.1. *The PFMP² tool can be grouped into 6 sections: (1) a PFMP, (2) a value chain analysis, (3) an overview of the total product offering, and (4) an overview of critical design issues.*

1. PFMP
2. Supply chain analysis
3. Overview of the total product offering
4. Overview of critical design issues

To each modelling element belongs a set of modelling rules, i.e. a modelling formalism or codex. For practical matters the modelling formalisms of the 6 different elements will be described one by one in the following. This leaves explanation of the linking modelling elements to the final sections of this chapter.

6.3. PFMP

This section is only a brief introduction to the PFMP tool. A more detailed description of the tool can be found in Harlou [2006]. The introduction given in this section serves only to present the tool developed in this research work in its totality and to enhance readability.

The basic modelling formalism used in the PFMP tool is based primarily on concepts from the system and object-oriented modelling paradigms.

System modelling

When modelling a product family it is critical to define what belongs to the family and what does not, i.e. the boundaries of the product family. Should for instance manuals, software, packaging, etc. be included in the model?

System theory provides support for defining the boundaries of the system that needs modelling. In system modelling objects are modelled as a set of elements and relations (fig. 6.2.) [Blanchard & Fabrycky, 1998], [Klir & Valach, 1965]. A system boundary separates the system from the surrounding environment. The system receives input from and delivers output to the surrounding environment.

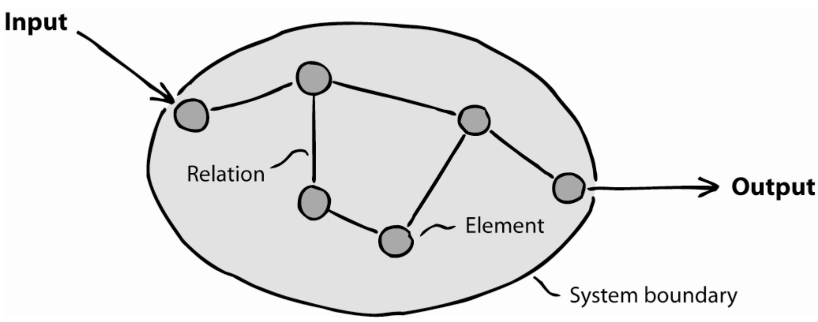

Figure 6.2. *A system is modelled as a set of elements and relations. The system boundary separates the system from its surrounding environment. The system receives input from and delivers output to the surrounding environment.*

System modelling distinguish between to types of attributes; structural and behavioural attributes [Blanchard & Fabrycky, 1998], [Klir & Valch, 1965]. Structural attributes describes how the system is build. Behavioural attributes describes the relation between input and output, i.e. what the system does.

Object-oriented modelling

Object-oriented modelling is a method for modelling knowledge and information in a given system by decomposing the system into sub-elements. The fundamental element in object-oriented modelling is the object. An object is defined as (one of many definitions) a concrete manifestation of an abstraction; an entity with a well defined boundary and identity that encapsulates state and behaviour; an instance of a class [Coad & Yourdon, 1998].

Abstraction is about ignoring those aspects that irrelevant in relation to the purpose, meaning that attention can be directed against the relevant aspects [Mathiassen et al., 1998]. That is, when modelling a concrete system less relevant aspects are left out of account. This is necessary in order to enable practical modelling of the relevant aspects.

In relation to the PFMP tool the key elements of object-oriented modelling are;

- *Class*
  Objects can be arranged in classes. A class is a model or description used to denote objects having similar characteristics (structure, behaviour and attributes). Identity, behaviour and attributes are described in general terms for each object in the class, but every single object has its own identity, concrete state and behaviour. The objects *'Mountain bike'*, *'BMX'*, and 'Tandem' all belong to the class of *bicycles*. This class serves as model for a number of different bicycles described by identity, state and behaviour [Mathiassen et al., 1998], [Coad & Yourdon, 1998].
- *Attribute*
  Attributes define the variety within a class [Coad & Yourdon, 1998]. The class of bicycles could for instance have the attributes 'colour' [red, green, blue] and 'number of speeds' [0, 3, 7, 10].
- *Instance*
  An instance is a specific object or example from a class. An instance has a identity, state and behaviour [Coad & Yourdon, 1998]. An instance of the class of bicycles could be a blue ten-speed mountain bike.

6.3.1. Basic PFMP modelling formalism

The PFMP basically consist of two structures; the *part-of* structure and *kind-of* structure (fig. 6.3.).

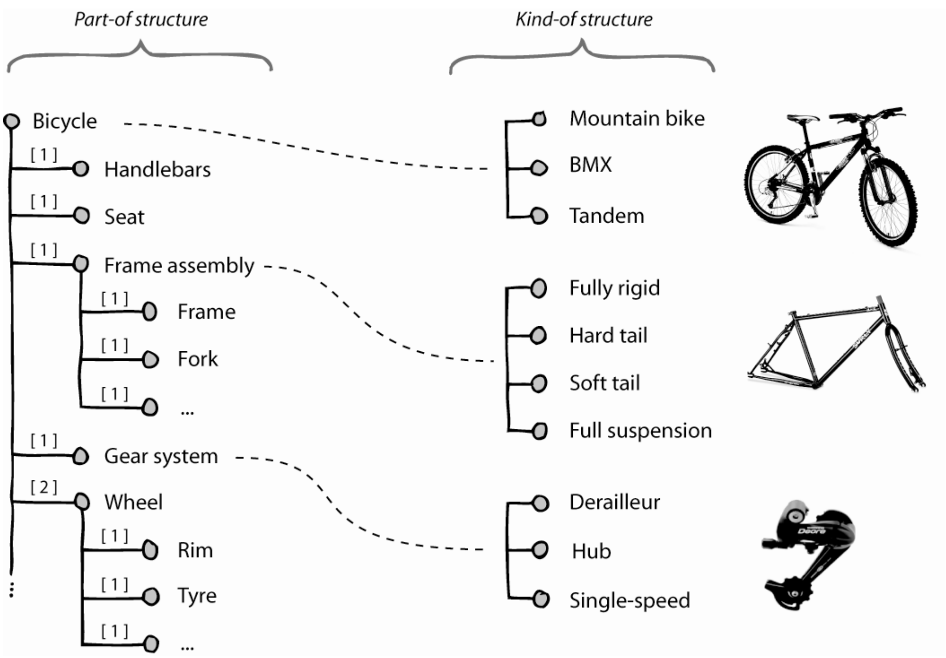

Figure 6.3. *A small example of the PFMP tool. It is in this application used to model the variety within a family of different bicycles.*

The part-of structure (to the left in figure 6.3.) describes the structure of the products and all the subsystem. Reading from the upper left corner all the parts and sub-systems of a bicycle are listed. The bicycle consists of two wheels, brakes, a frame, a gear system, etc. and the wheels consists of a rim, a tyre, etc.

The kind-of structure (to the right in figure 6.3.) describes variants of the parts and sub-systems. Sub-system like the frame, the wheels, and the gear system has kind-of structures to the right. For instance three types of gear systems exist.

Class definition

In the PFMP tool a class can be a part, a system of several parts, or a group of descriptive attributes. Each class is assigned a distinct name for unambiguous identification. A class is indicated using a black dot and the class name is written in bold black next to this dot (fig. 6.4.).

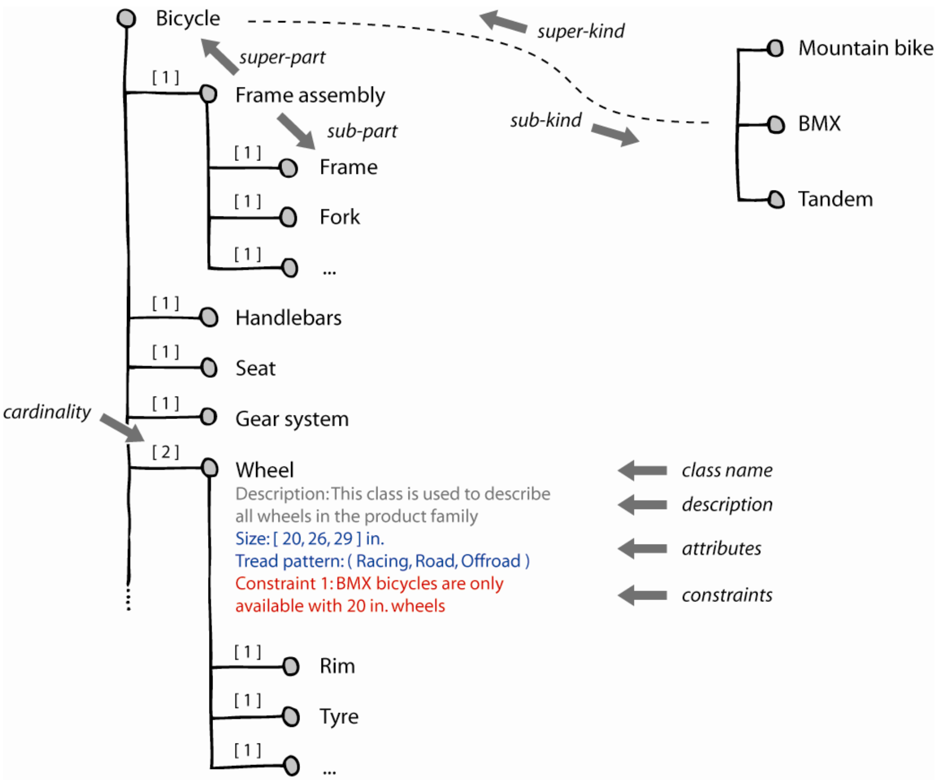

Figure 6.4. *Each class is given a distinct name for identification. If necessary a supplementary description can be added beneath. Furthermore classes can include attributes and constraints.*

When necessary it possible to add a supplementary description of the class beneath the class name.

The classes are used to describe a hierarchy in the part-of and kind-of structures. A class can consist of one or more classes. Hence, the class below another class is called sub-part and the class above another class is called super-part (fig. 6.4.).

Likewise, sub- and super-kinds represent specialisation and generalisation of a specific class.

Classes in the part-of structure are furthermore allotted a so-called cardinality. The cardinality denotes how many of a particular sub-part that a super-part consists of. A bicycle for instance consists of one frame assembly, one set of handlebars, two wheels, etc. - a wheel consists of one rim, one tyre, etc.

It is important to notice that the cardinality refers to the super-part. Therefore, the cardinality of the 'rim' is [1] because it only takes one rim to build a wheel. Still, it takes two wheels and consequently two rims to build a bicycle, thus the cardinality of 'wheel' is [2]. The cardinality of 'rim' remains [1] because it refers to the super-part 'wheel' and not the class 'bicycle'.

Attribute definition

If the class include attributes they ate listed in blue font below the class name and the contingent description of the class (fig. 6.4.). The PFMP makes use of four different types of attributes:

- *Identifier*
  An attribute of the type identifier is expressed using a string of text, e.g. colour: (red, green, blue)

- *Integer*
  The set of integers is described as the natural numbers (0, 1, 2, 3, …) and their negatives (0, -1, -2, -3, …), i.e. (…, -3, -2, -1, 0, 1, 2, 3, …). Integers can be expressed as single numbers (e.g. [3]), intervals (e.g. [3-6], or a fixed set of numbers (e.g. [1, 3, 4, 6])
- *Real*
  The set of real numbers include rational (e.g. 23, -23/129, etc.) and irrational numbers (e.g. π). Real numbers can be described by an infinite decimal representation (e.g. 3,142637625…). Like integers, real numbers can be expressed as single numbers (e.g. [1.8]), intervals (e.g. [1.6 ... 2.3]) or a set of fixed numbers (e.g. [1.6 , 1.8 , 2.0 , 2.3])
- *Boolean*
  An attribute that has the nature of being true or false is denoted as boolean, e.g. Air-conditioning: (true, false)

Constraint definition

Constraints are limitations for how the elements in the PFMP (i.e. classes and attributes) can be combined. Constraints are always declared in a class and even though a constraint refers to more than one class it is only declared once. Constraints are declared in red font beneath the class name and the contingent description and attributes. The PFMP include four types of constraint expressions:

- *Verbal*
  The constraint is expressed verbally (e.g. "A mountain bike has offroad tread tyres")
- *Logic*
  The constraint is expressed using logic mathematical notation (e.g. "Mountain bike => Offroad tread tyres")
- *Calculation*
  The constraint is expressed as mathematical equations (e.g. "Bicycle_weight = Frame_weight + Wheel_weight")
- *Combination table*
  Combination tables are used to state how components can be combined (fig. 6.5.). The combination table is a means to manage multiple constraints and in this way replace formulation of verbal, logic and calculation constraints.

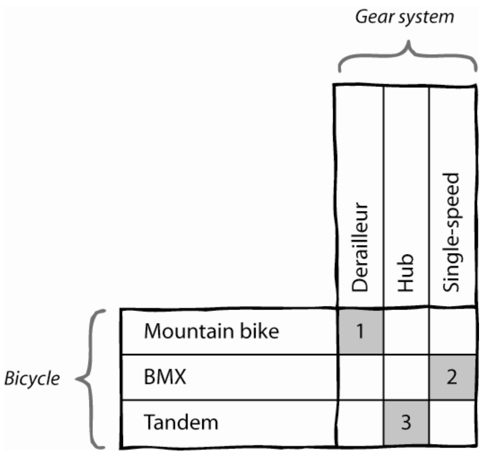

Figure 6.5. *The combination table expresses how classes and attributes can be combined. This simple example shows how the different gear systems are belong to different types of bicycles; (a) constraint 1: Mountain bikes has derailleur gear,(b) constraint 2: BMX bicycles are single-speed, and (c) constraint 3: Tandems are equipped with a hub gear system.*

A constraint is given a distinct number for unambiguous identification. This enables the possibility of having a more detailed documented description of the constraints in separate systems, which can easily be located using the unique constraint number.

6.3.2. Different views on the product family

In accordance to Andreasen et al. [1996] the PFMP tool introduces three views on a product family:

- *Customer view*
  The customer view should – as the name imply - describe the product family as seen from the customer's point of view. This should therefore explain what features and application characteristics that gave the customer's interest
- *Engineering view*
  The engineering view should describe the product family from an engineering point of view and should consequently describe the structure of organs and the variety of organs in the product family, i.e. explain how the product family work and how it vary
- *Part view*
  The part view should describe the product family from a physical point of view, i.e. explain how the physical entities (parts and assemblies) are structured and they vary

The basic PFMP modelling formalism as described in the previous section ('6.3.1. Basic PFMP modelling formalism') is valid for all three views. In the following is described how the three views are treated separately.

Modelling the 'Customer view'

The customer view should describe the product family as seen from the customer's point of view. Customers are presumably most interested in the behaviour of the products, but might also have preferences about structural aspects of the products. Accordingly, the customer view includes both behavioural and structural aspects of the product family.

The modelling formalism used in the customer view enables modelling of three different aspects of a product family:

- *Technical process modelling*
  Behaviour of the product is closely related to the customer's application of the product. Modelling the technical process system as presented in the theory of technical systems [Hubka, 1973] is one way to model the application of the products. Not only the technical system (the product) but all four systems of a technical process system should be modelled, i.e. also the human system (the operator), the environmental system (influence from the surroundings), and the technical process system (the meeting). Furthermore, operands should also be included in the model.
  The formal PFMP representation of a technical process is illustrated in figure 6.6.
- *Interface modelling*
  The customer's application in which the product is used in often demand certain features in the product, i.e. demands to the interface between the product and the customer's application. In the PFMP tool interfaces are modelled as separate classes in the part-of structure and variety among the interfaces is presented in the kind-of structure according to basic PFMP modelling formalism.
  The formal PFMP representation of an interface is illustrated in figure 6.6.
- *Feature modelling*
  A third opportunity is to model the variety features that are offered to the market. Features are modelled as classes in the part-of structure - similar to the way interfaces are modelled – and the variety of features is presented in the kind-of structure.
  The formal PFMP representation of a feature is illustrated in figure 6.6.

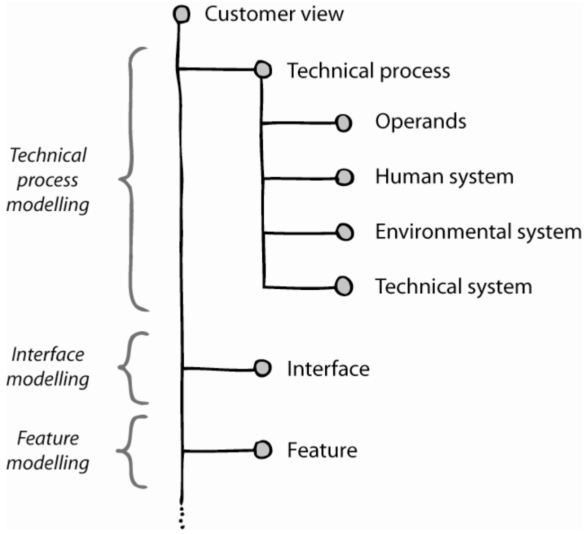

Figure 6.6. *The customer view modelling formalism. The formal representation of technical processes, interfaces, and features in the PFMP.*

Figure 6.7. gives an example of how the modelling formalism is applied on a bicycle product family in order to model technical processes, interfaces, and features.

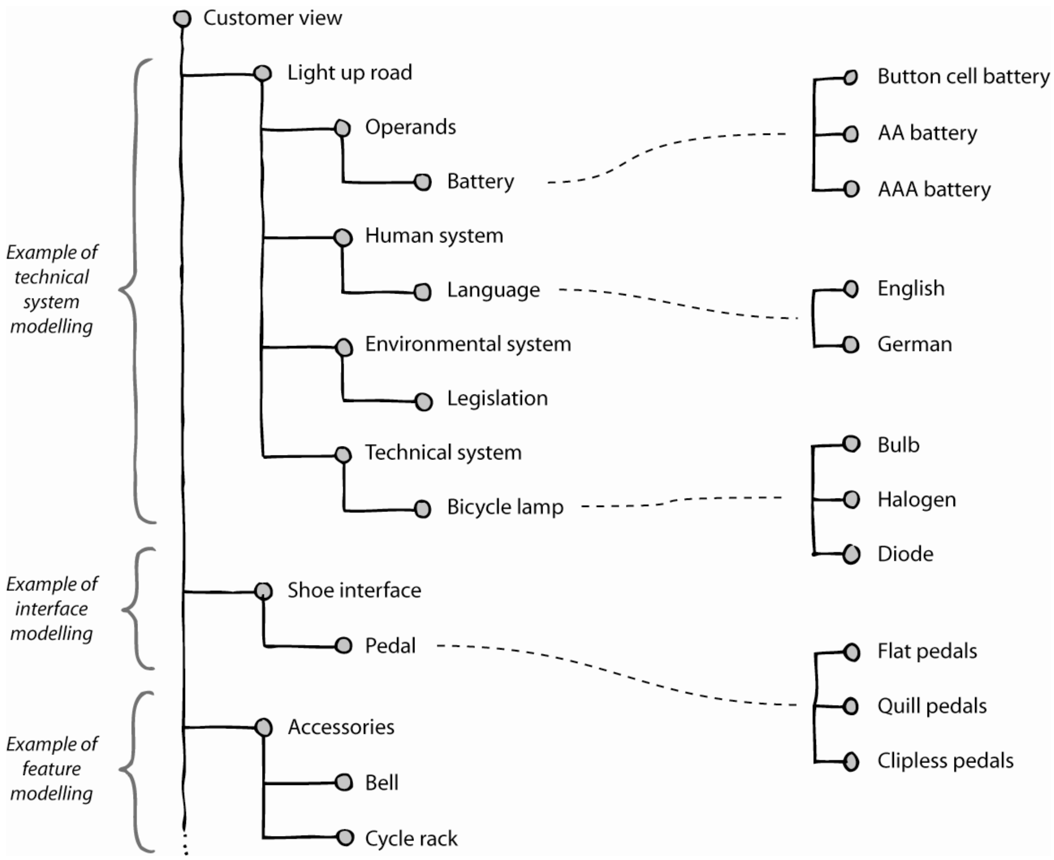

Figure 6.7. *Example of how technical processes, interfaces, and features can be modelled when applying the customer view modelling formalism on a family of bicycles.*

Modelling the 'Engineering view'

The objective of modelling the product family from an engineering point of view is to describe how the products in the product family work from a functional point of view and to present the functional variety.

The modelling of the engineering view normally has its starting point in identification of the main functions of the products. Subsequently, the carriers of these functions – the so-called organs – can be determined. Main functions are then decomposed into to sub-function and the appurtenant sub-organs are identified until all relevant functions and organs have been described.

The modelling formalism used in the engineering view enables modelling of organs in the product family:

- *Organ modelling*
  The identified organs are represented as classes in the PFMP in accordance to the basic PFMP modelling formalism, i.e. organs are modelled as different classes in the part-of structure and variety among the organs are represented in the kind-of structure

In figure 6.8 is shown a part of the engineering for family of bicycles.

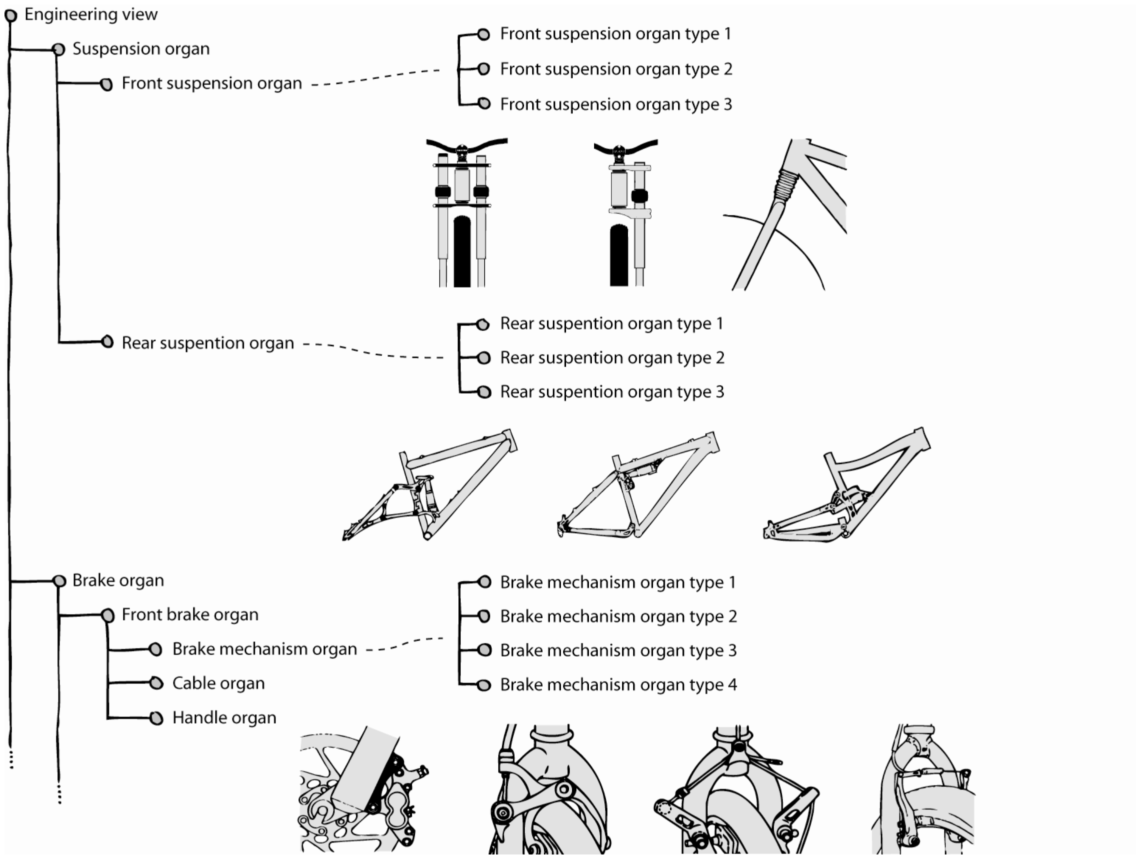

Figure 6.8. *Example of how the functional variety in a bicycle product family is modelled in the engineering view.*

Notice that organs often are best represented using simple drawings. This is especially a consequence of the fact that organs are not build from physical parts but from the so-called material areas [Andreasen, 1980].

Modelling the 'Part view'

The purpose of the part view is to model the physical structure of the products in a product. The part view is consequently the most tangible view of the three views in the PFMP and the contents (classes) are the physical components and assemblies of the product family. The part-structure in the part view can be perceived as a generic bill-of-material that valid for all the products that belong to the modelled product family, i.e. a superimposition of all products' structures. The kind-of structure represent the variety of components and assemblies.

Figure 6.9. shows an example of a part view modelled for a bicycle product family.

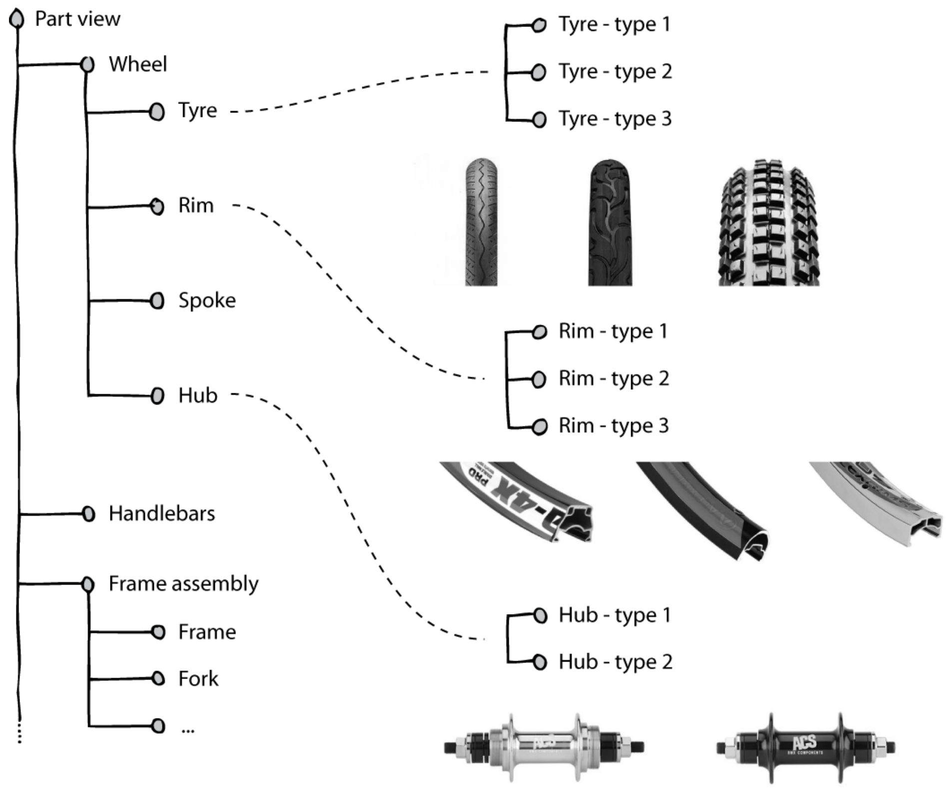

Figure 6.9. *Example of a part view modelled for a bicycle product family.*

6.3.3. Coherence in the customer, engineering and part view

The three views are causally linked [Hubka, 1973], [Andreasen, 1980], meaning that elements in the customer view are realised by the means of elements in the engineering view which again are realised through the physical components in the part view. The causal relations are modelled in the PFMP in order to describe how features in the customer view is realised physically by the means of organs in the engineering view and components/assemblies in the part view, and also to describe how the physical components/assemblies contribute to the realisation of features in the customer view, i.e. how the physical parts/assemblies add value to the customer (fig. 6.10.).

The causal relations provide an indication of engineering complexity within the product family. If a feature in the customer view links to several organs in the engineering view and each of these organs again link to several assemblies in the part view, it indicates that the product architecture is relatively integral as opposed to modular [Ulrich, 1995]. Deriving product variety based on integral product architectures will normally lead to great complexity because even the slightest change in features in the customer view has comprehensive consequences in the physical realisation of the product.

In this research work causal relations are relevant for two reasons:

- Identification of waste
- Tracking of consequences of changes

The two bullets are described further in the following sections.

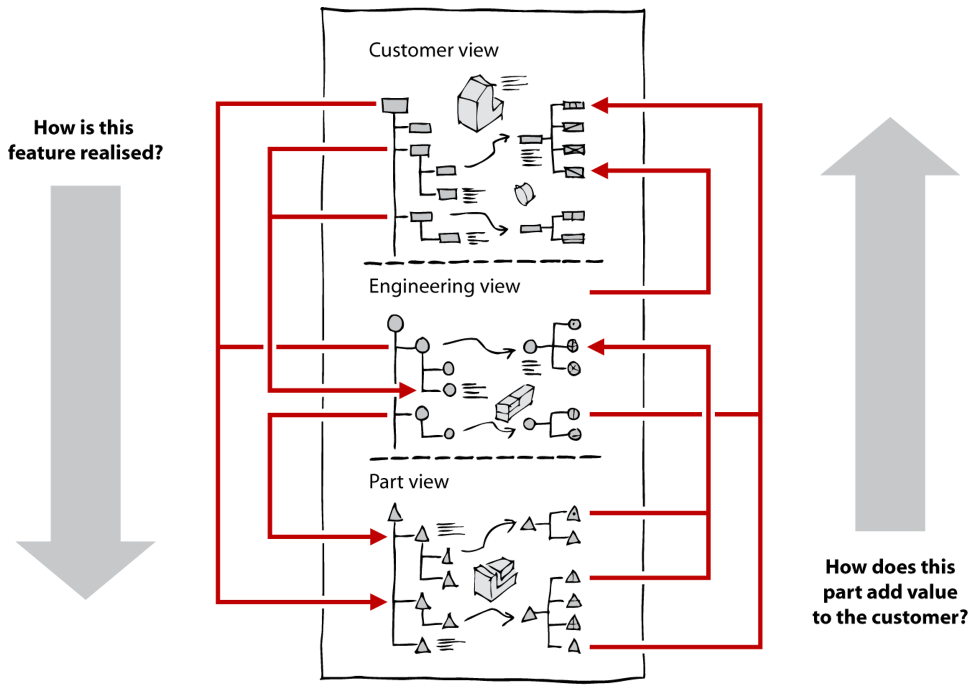

Figure 6.10. *The causal relations are modelled in the PFMP in order to (a) describe how features in the customer view are realised physically by the means of organs and parts, and (b) describe how the physical parts add value to the customer [Harlou, 2006].*

Identification of waste

As it is described earlier one of the tasks the tool should support is identification of potential waste. Causal can help indicate two types of waste:

- *Redundancy in solutions*
  Redundancy in solutions is present if the same feature in the customer view is realised in number of different ways, i.e. different solutions are used to solve the same problem. In this context it should be emphasised that the customer view should describe the product family as seen through the eyes of the customer and redundancy occurs when the customer (not the designer) can't tell the different solutions apart.
  An example of redundancy in solutions is illustrated in figure 6.11.
- *Non value-adding elements*
  Non value-adding elements are - in this context - elements that does not contribute to the realisation of features in the customer view, i.e. organs that doesn't link to features in the customer view or parts/assemblies that doesn't link to the customer view, either directly or indirectly through organs.
  An example could be that the company mounts bottle cages on the BMX bicycles even though it is not requested and therefore doesn't add any value to the customer.

Consider the example illustrated in figure 6.11. According the customer view the customers only demand four variants of different suspension setup but the company offer a quantity of 16 suspension solutions (if solutions with no suspension in front and/or rear are included). In principle, the company could manage with only one solution for front suspension and rear suspension, respectively.

If the example in figure 6.11. were to be detailed further, it might reveal other reasons for having several solutions principles. It is presumed that the different solutions do have identical characteristic regarding price, robustness, and weight, which probably all are features of a bicycle that would be included in the customer view. This would contribute to the network of causal relation and hereby complicate identification of redundancy in solutions. Still, the question "do we really need all these different solutions" can be of great value and the modelling of causal relations helps not only to expose but also to answer such questions.

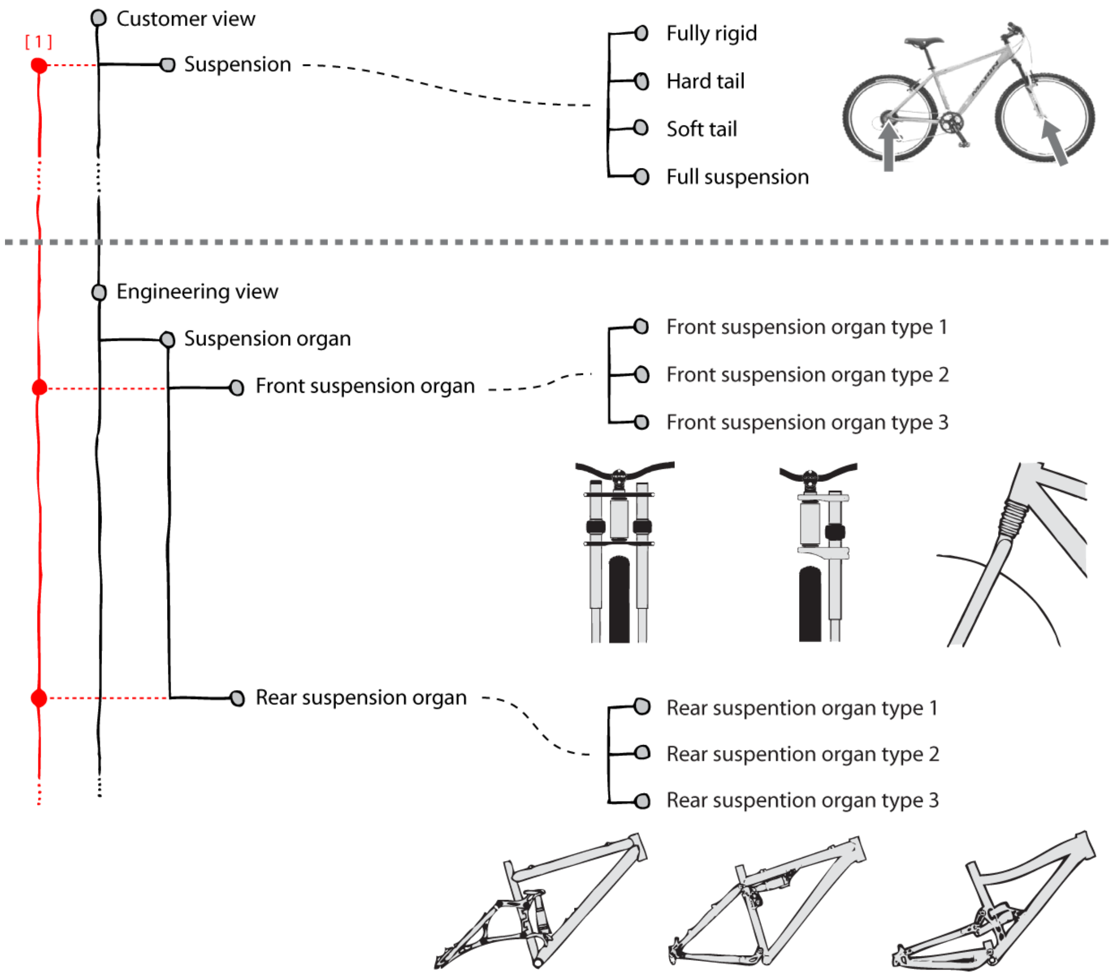

Figure 6.11. *Example of redundancy in solutions illustrated using a bicycle family. Note that the customer view indicate that the customers demand four choices in suspension setup but the company provides quantity of 16 combinations of setup including no suspension in front and/or rear.*

Tracking of consequences of changes

Harlou [2006] mentions two reasons for indicating the causal relations in the PFMP:

- *Changes in the customer view*
  If the company identify the need for a new feature or for changing a feature, for instance due to a specific customer request, it is not only convenient to be able to track how the feature is realised physically, it can also be a way to limit the growth of complexity because it urges the designer to use similar solutions to realise the new/changes feature instead of developing new.
  Tracking consequences of changes in the customer view might is not particular relevant to this research work (re-design of the product family), as it is to the day-to-day management of the product family.

- *Changes in the product family*
  Being able to track the consequences in the customer view of changes made in the product family (i.e. the engineering view and part view) is critical in the process of re-designing the product family. If the company for instance has the desire to discontinue the relationship to a specific sub-supplier in the attempt to reduce the number of sub-suppliers, it could results in changes of certain parts and/or assemblies and then it critical to understand the consequences of such changes – sometimes even the slightest changes means the world to the customer.

Since the purpose of modelling the product family is to establish a better foundation for making decision about re-design of the products understanding the consequences of such design changes is of most critical importance. Modelling the causal relations provide a way to track the consequences of the design changes.

The causal links are modelled in a grid system to the left of the part-of structure in the PFMP (see fig. 6.11.). Each vertical line in the grid represents a causal link. Dots on the vertical lines (causal links) indicate the elements in the part-of structure that are influenced by the specific causal link. The causal links are numbered (just like constraints) for unambiguous identification. Again, this makes it possible to refer to a more thorough description of the causal link that is documented in a separate system.

6.3.4. Conclusion on the PFMP

The PFMP modelling tool as described above contributes to meet the demands that have been put on this research work (see section '4.3. Requirements') in a number of ways;

Product structure

First and foremost the PFMP tool is a method to present the structure of the products in the product family seen from three different viewpoints, i.e. customer, engineering, and part view.

The object-oriented and system modelling approach used in the PFMP tool enables modelling of a generic product structure valid for all products (part-of structure) and also modelling of the variety within the product family (kind-of structure).

Furthermore, the PFMP tool provides a method to manage constraints within the product family.

Customer perceived product offering

The customer view in the PFMP should present the product family as seen from the customer's point of view, including the variety offered in the product family.

Modelling constraints in the customer view together with the part-of and kind-of structure presents not only the diversity in the product offering but - just as important - also the limitations, i.e. an overview of the total product offering as it is perceived by the customers.

Causal links

The formalism for modelling causal links (fig. 6.11.) varies a bit from the original representation form as it was presented by Harlou [2006] by including an identification number for each link, which makes it possible to refer to more detailed descriptions of the causal links managed in separate systems.

Still, it should be noted the graphical representation form used in this research work and the one used by Harlou [2006] has its limitations regarding the number of links that can reasonably be managed. Not that the technique has any technical limitations in that sense, but if too many links are included in the model the effects of the visual representations form could suffer.

The key is to include a balanced number of causal links that explain how the most critical features in the customer view are realised physically. This will in the re-design phase help keep focus on what provides the most value to the customer.

Value of variety

The combination of object-oriented modelling and modelling the causal links is a powerful support to indicate value of variety in the product family.

In relation to re-design of a product family identification of potential waste is of prime interest (see section '4.1. Reference model') and in that respect identification of non value-adding variety becomes relevant.

As discussed in section '4.3.2. Value of variety' a prerequisite for being value-adding is that the variety most be visible to the customer and also considered as a selection parameter. If it is assumed that the customer view presents the product family objectively as seen from the customers' point of view then a mismatch between variety in the customer and variety in the engineering and/or part view indicates redundancy in solutions (fig. 6.11.) and therefore non value-adding variety, i.e. the company offer multiple solutions that the customers either perceive as identical and/or they are indifferent to whether they get one or the other.

6.4. Supply chain analysis

A supply chain is an aggregated and end-to-end view of the buy-side and sell-side relationships of an enterprise [Lambert, 2000] (fig. 6.12.).

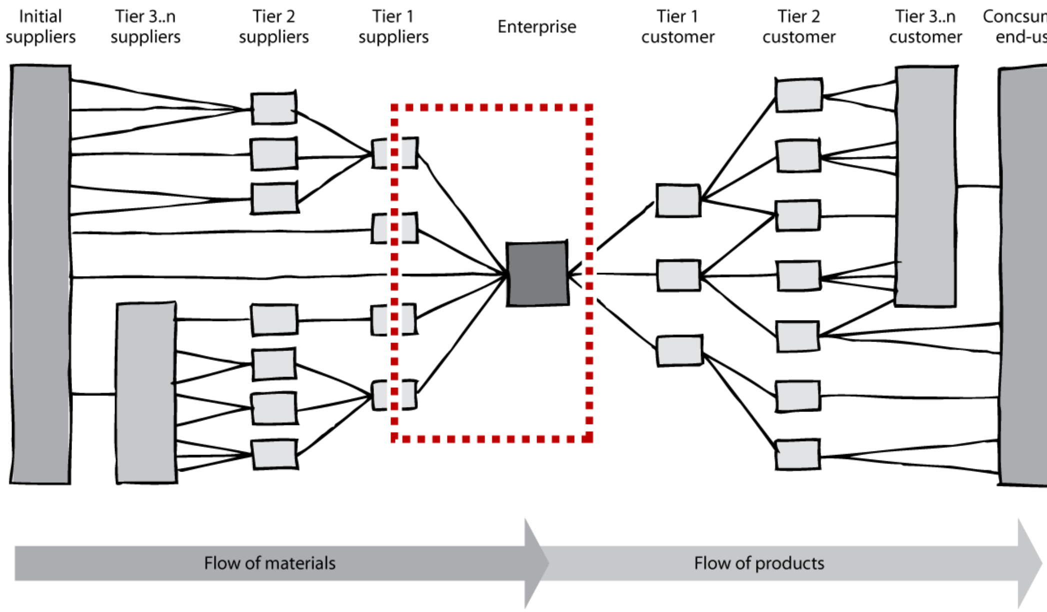

Figure 6.12. *Conceptual model of the supply chain. A supply chain is the network of facilities and distribution capabilities an enterprise uses to: (a) "Source" (or "procure") raw materials (chemicals, ores, grains, ...) or components, (b) Transform the materials or assemble the components into products, and (c) Deliver the products to customers (indirectly through distributors or stores or directly to the purchaser) [Lambert, 2000].*

A supply chain is the system of organizations, people, technology, activities, information and resources that is required to bring a product or service from supplier to the end customer. Supply chain activities in the widest sense transform natural resources into raw materials, raw materials into components, and finally components into finished products that are delivered to the customers.

Typical supply chain activities include production, planning, purchasing, materials management, distribution, customer service, and sales forecasting. As the objective of the supply analysis is to examine the company's ability to produce product variety effectively, the focus of the analysis is the buy-side of the supply chain, i.e. the activities that are needed in order to derive the current variety of products. Thus, activities regarding distribution, customer service, etc. are not included in the analysis.

Furthermore, the analysis of the supply chain will in this research work is limited to deal with activities within the company (enterprise) and activities connected to purchasing from tier 1 suppliers (illustrated by the dotted red box in figure 6.12.).

In lean production value stream mapping is used for identification of waste, but generally, lean production and value stream mapping only consider waste directly linked to the production setup, and do for example not consider aspects like unnecessary process variety as a consequence of product variety and accompanying complexity that has to be managed.

In value stream mapping a product family is defined as a series of products (or services) that pass through the same processing steps [Sayer & Williams, 2007]. This shows that value stream mapping focuses solely on the production and evade the need for managing variety of processing steps.

The rationale underlying the modelling of the supply chain is to study the consequences product variety and the accompanying complexity has in the production setup. That is, understanding the variety of processing steps that are needed to manage the variety within the product family (also products that pass through different processing steps).

Similar to the way the PFMP illustrated variety within the product structure in the part-of and kind-of structures by superimposing the structures of all products, it is the intension to show variety in the supply chain by modelling each product's supply chain individually and subsequently superimpose them.

6.4.1. Flow of materials

In order to link the supply chain to the product's design it is chosen to develop the model with intention to examine the flow of the variety of physical parts and assemblies through the processing steps in the supply chain – i.e. the flow of materials.

Basically, flow of materials can be studied from two perspectives;

- Layout perspective
- Time perspective

Layout perspective

Studying the flow of materials from a layout perspective means that you study how the physical parts and assemblies are moved around the factory floor, room, world, etc. In Lean toolbox layout diagrams (or spaghetti diagrams), like the one in figure 6.13., are used to map the traffic or movement of materials or people.

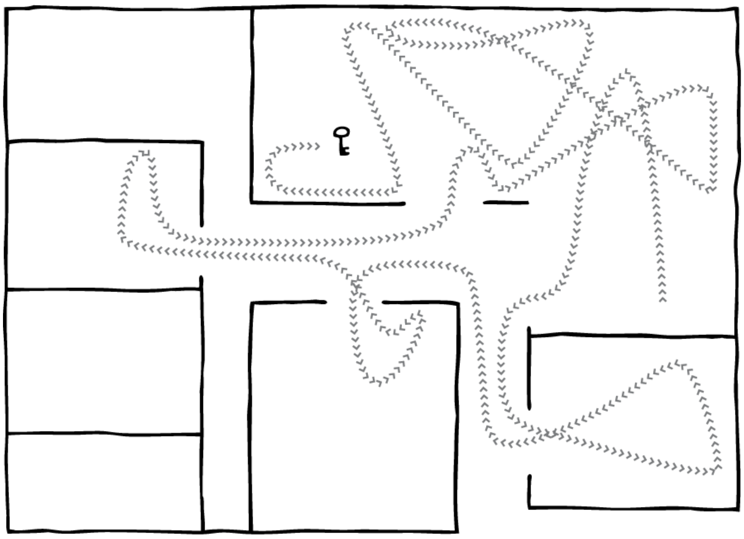

Figure 6.13. *Example of a layout diagram illustrating a person looking his/her keys around the house. The spaghetti diagram is used to track the movement of physical parts and assemblies around the factory floor [Sayer & Williams, 2007.*

The example in figure show the movement of a person that has misplaced his/her keys and is looking for them around the house.

The way layout diagrams are used in lean is by observing (i.e. following) the object on its way around the factory floor and draw the diagram as you go along. In that way the layout diagram is used more as a tool to identify unexpected and unplanned movement rather than mapping the planned flow of materials. For instance the layout diagrams are used to illustrate how much time a worker waste searching for misplaced tools etc.

The layout diagram can also be used for logistic optimisation of the planned traffic of parts and assemblies, but basically this can be done without regard to the design of the products, as normally only few constraints exist between the products' design and the physical layout of the production. Since we are interested in understanding the dispositional relations between the products and the production the flow of material should not be studied from a layout perceptive.

Time perspective

Instead, the flow of materials should be studied in a time perspective, i.e. the various processing steps are placed in relation to a time scale rather than the physical position in the factory.

The assumption that the presence of dispositional relations between the products' design and the supply chain should become more apparent when studied in a time perspective is based on the fact that the product design normally determines the sequence of processing steps in the supply chain. Consequently, it is not possible to rearrange the processing steps in time (without according product changes) in the same way it possible to rearrange the physical layout of processing steps without regards to the products' design.

Examining the flow of materials in a time perspective makes it possible to study the expansion of variety throughout the supply chain. As described in section '3.3.2. Mass customization' postponement of the point of variegation is a means to limit the complexity that needs handling throughout the supply chain, simply because the variety – and therefore the accompanying complexity – is created at a later stage in the supply chain. It is interesting to study how the variety develops throughout the supply chain as we are trying to identify opportunities to postpone variegation.

The production variety funnel as was illustrated in figure 5.19. is used to indicate the variety that has to be managed at different stages in the supply chain [New, 1974].

The production variety funnel only shows the level of variety at each stage; whereas we want to understand what is preventing postponement of the point of variegation.

6.4.2. Basic supply chain modelling

The model should basically present the flow of materials through the various processing steps that are needed to complete a finalised product in a way that makes it possible to track the elements in the PFMP's part view (i.e. parts and assemblies) on the way through the supply chain.

Figure 6.14. shows a part of the flow of materials for a single bicycle.

As indicated by different shades of grey in figure 6.14. the model distinguishes between different types of processing steps:

- *Purchasing*
  As indicated in the conceptual model in figure 6.14. a supply chain (or at least the part considered in this study) begins with the procurement or purchasing of raw materials, components, modules, etc. The purchasing steps are used to identify the parts that are input to the supply chain.
- *Fabrication*
  The fabrication steps denote processing steps that transform material into another state. Typical fabrication steps are milling, cutting, moulding, etc.
- *Assembly*
  The assembly steps denote processing steps where parts and/or sub-assemblies are joined together. Assembly processes are either reversible or irreversible, i.e. the assembly can be disassembled or not. Reversible assembly processes are typically simple mechanical joints such as nuts & bolts or various snap locks. Examples of irreversible assembly processes are welding and soldering.
- *Testing*
  In some cases testing of the products quality is critical and should consequently be treated similarly to way fabrication and assembly processes are treated.

In order to present the variety of processing steps within the supply chain we basically drawn up the flow of materials for each every product variant and superimpose to expose varieties and commonalities.

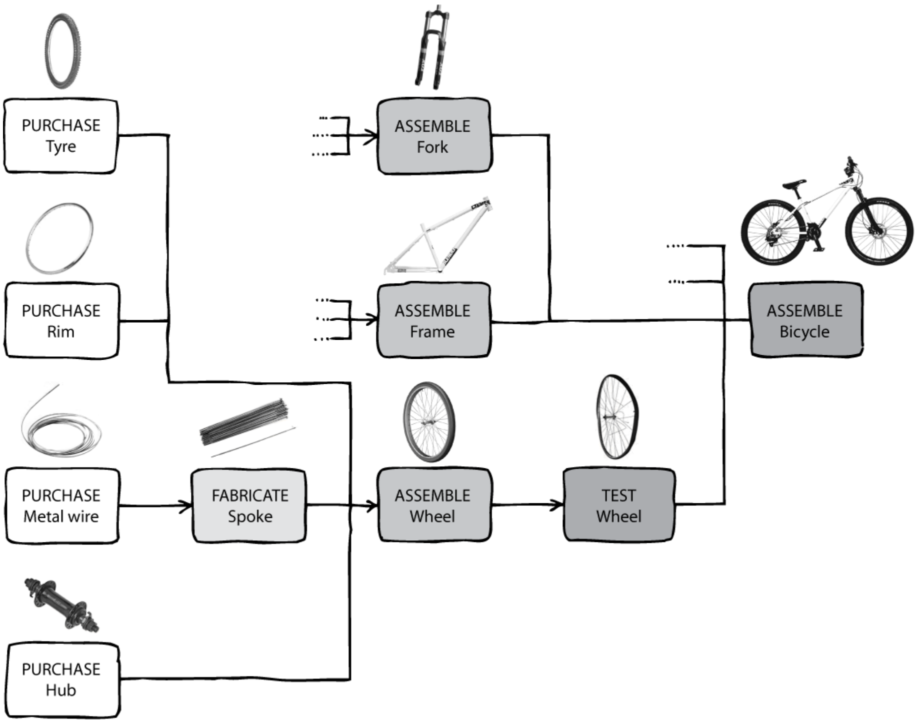

Figure 6.14. *Part of a supply chain that shows the flow of materials through the process steps that are needed in order to complete a finalised bicycle.*

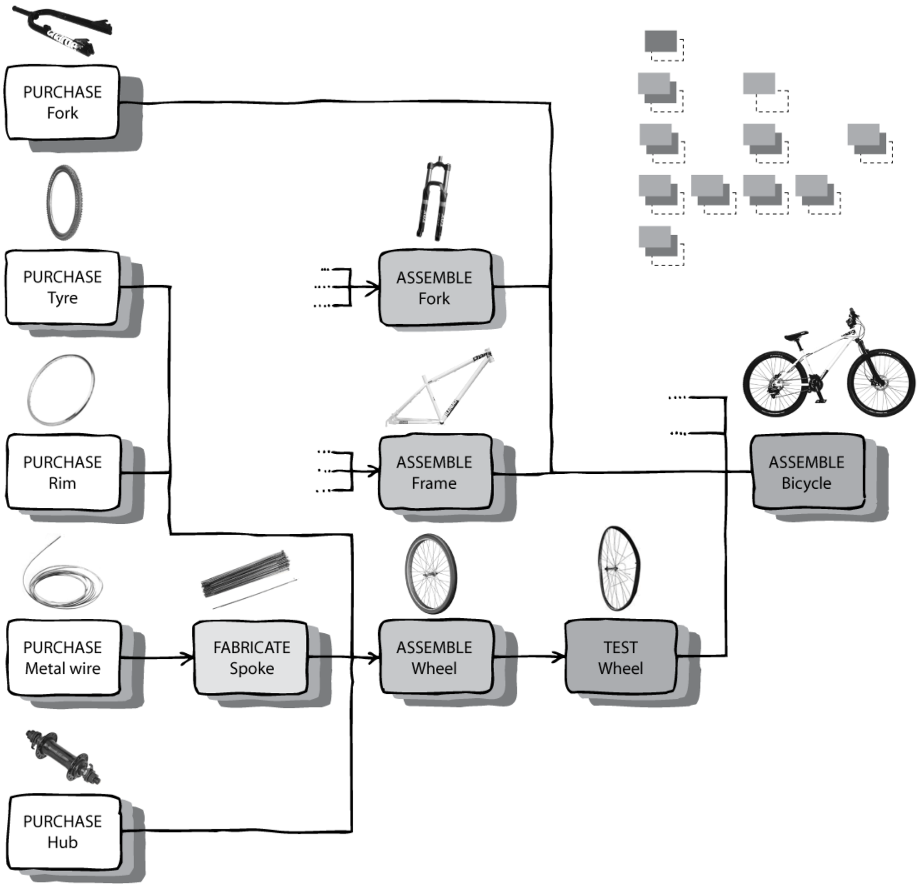

Figure 6.15. *Superimposing the individual supply chain of two different bicycles exposes commonality and variety among the two supply chains.*

In figure 6.15. is shows an example of superimposed supply chains for two different bicycles. The one bicycle (green) is equipped with a suspension fork that needs to be assembled from various purchased parts (these parts are not indicated in the figure). Consequently, this bicycles supply chain includes the process step *'Assemble FORK'*. The other bicycle (blue) has a rigid fork. This fork does not need any further processing steps (assembly) and is brought directly in to the final assembly of the bicycle. Instead, this bicycles supply chain only includes the process step *'Purchase FORK'*, and not *'Assemble FORK'*.

6.4.3. Modelling the processing steps

The modelling formalism used to model the processing steps in the supply chain in primarily based on the modelling of technical processes as presented in the theory of technical systems [Hubka and Eder, 1988] (section '3.2.1. Theory of technical systems').

Figure 6.16. illustrates how the processing step *'Fabricate GEAR WHEEL'* from the supply chain can be viewed as a technical process.

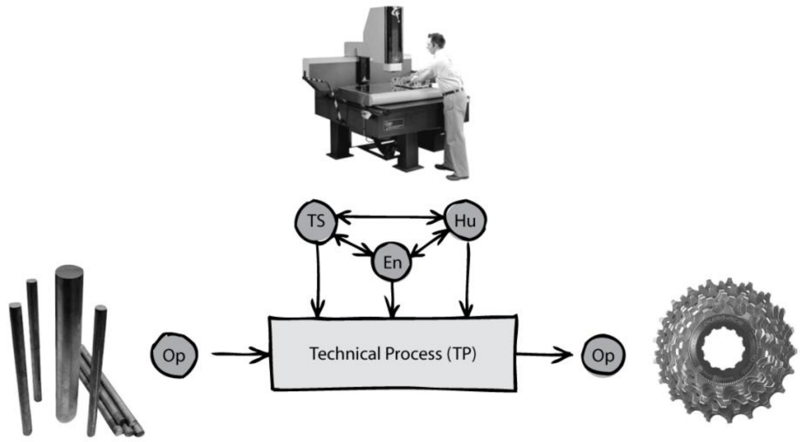

Figure 6.16. *The processing step 'Fabricate GEAR WHEEL' viewed as a technical process [Hubka and Eder, 1987]. The element in the model are: the technical system (TS) is the CNC milling machine, the human system (Hu) is the human operator, the environmental system (En) is for instance the electrical power grid that is necessary for the machine to operate, the material operands (Op) are in input state the aluminium rods and in output state the machined gear wheel.*

The technical process (TP) is a simple input/output model that illustrates the transformation of the input operands' state. The operands are divided into the three categories material, energy, and information. The example shown in figure 6.16. has an aluminium rod as material input operand, electricity as energy input, and for instance machine settings and a CAD model of the gear wheel as information input. The technical process transforms the state of these input operands. The material input (aluminium rod) is transformed into a finished gear wheel and aluminium shaving. The energy input (electricity) is transformed into heat in the aluminium. The output information of the process is for instance data feedback from the milling machine (the CAD model is not transformed in the process).

As it is mentioned earlier focus will be on modelling the flow of materials in order to link the supply chain model to the PFMP. Accordingly, the supply chain model will only encompass the material input and output operands of the technical process.

When modelling the supply chain for an entire product family many of the processing steps will having multiple inputs and outputs. Because the output from one processing step normally serves as input to another process (fig. 6.17.) it becomes redundant to model input as well as output for each process.

Value stream mapping (VSM) [Womack & Jones, 2003] also distinguishes between flow of material and flow information (energy is not considered). The flow of materials is indicated using standardised symbols to explain how the materials are handled between the process steps. That is between two processing steps VSM is always indicated an inventory, i.e. storage of materials (raw materials, purchased parts, semi-manufactures, finished goods, etc.), plus it is indicated whether the flow to and from the process are regulated by push or pull of materials (see section '3.4.2. The concept of waste').

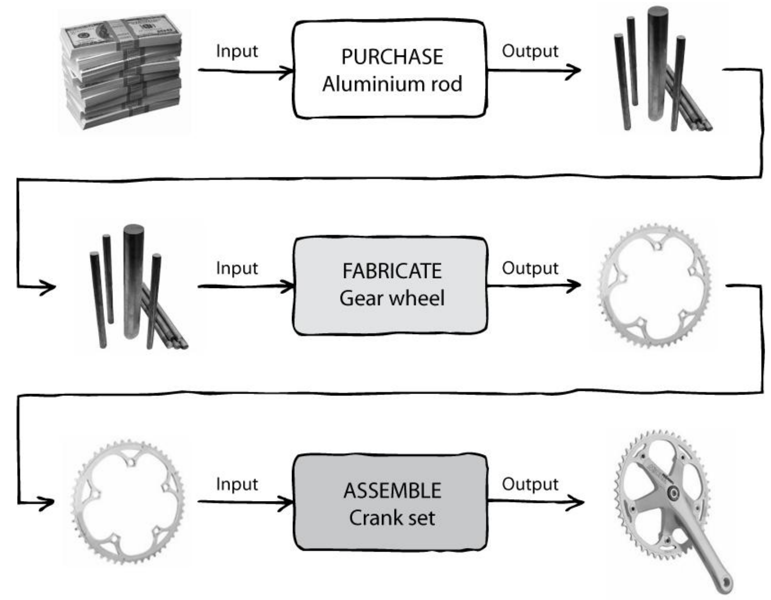

Figure 6.17. *Flow of materials. The output of from on process step serves as input to next following process step, i.e. the aluminium rods that are the outcome of the 'Purchase ALUMINIUM ROD' process are input to the 'Fabricate GEAR WHEEL' process, etc.*

In the model presented there will be no distinction between different kinds of inventory or whether processes are push or pull regulated as it is not considered as crucial information in relation to a re-design process. Anyway, modelling inventory between processing steps enables modelling the flow of materials without redundant notation of input and output (fig. 6.18.).

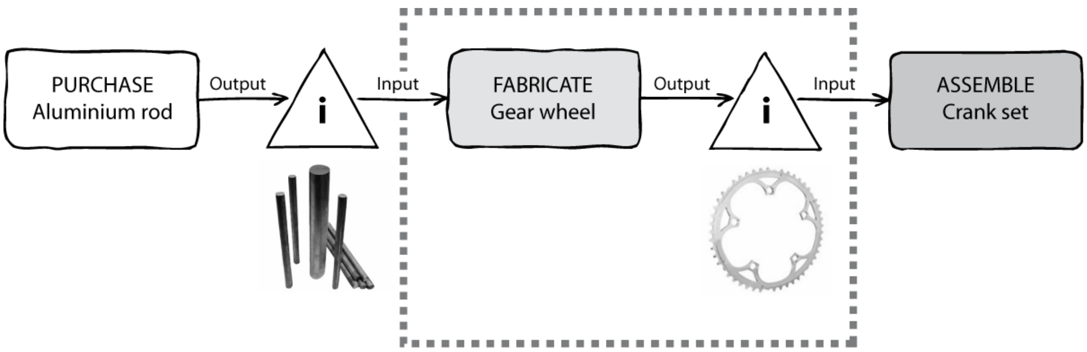

Figure 6.18. *Modelling inventories between the processing steps enables modelling of the flow of materials without redundant notation of input and output. The dotted box indicates the basis for the modelling elements used in the subsequent supply chain analysis.*

The dotted box in figure 6.18. illustrates the modelling elements used in the supply chain analysis. The modelling elements include a description of the actual process and the output (i.e. the subsequent inventory) of the processing step.

When discussing variation in processes it is not sufficient to only consider the technical process together with input and output (fig. 3.1.). Such an approach will only describe what happens in the processing step but it will not tell anything about how it happens, i.e. who, what, where, when?

Besides the 'when' (which is sufficiently clarified by the relative position in the supply chain model) these questions can basically be answered by understanding the operators of the technical process (i.e. the technical system (TS), the human system (Hu), and the environmental system (En)) as it is the interplay between these that create the effects necessary to carry out the technical process.

Similar to the way the product elements are arranged in classes it is possible to arrange process steps in classes (super- and sub-classes), and just like attributes are used to describe variety within a given class of product elements in the PFMP attributes are used to describe the variety within a class of processes, i.e. attributes are used to describe the variety within the process operators.

As the descriptions should merely serve as a means to make an overall distinction of variety in between processes within a class it is often sufficient to use relatively simple attributes to describe the process operators (TS, Hu, and En). The appropriate level of detail is dependent on the specific application, but the general description of the process operators include:

- *Technical system (TS)*
  The technical system used in the processing step is typically described by the machine performing the process or by the utilised technology. Assembly of to items can for instance be performed using different welding technologies (SMAW, TIG, MIG, FCAW, etc.) and in many cases it is sufficient to describe the technology as it is usually the technology rather the specific machine that sets requirements to the product design. Again, the necessary level of details is determined by the specific case.
- *Human system (Hu)*
  Ideally, the human system is described by the persons involved in performing the process, i.e. how many persons are required, what competencies are required, etc. By default, the model simply indicates the level of automation. Only in cases where it is considered that extraordinary skills are needed to perform the process.
- *Environmental system (En)*
  The environmental system is described by the surroundings that are necessary in order to perform the process (e.g. electrical power supply, supply of pressurised air, etc.). Typically, these are details that have no link to the product design and consequently no relevance to this type of analysis. Therefore such environmental requirements are only indicated in the model when it is considered relevant to the product design – for instance if a process requires particular clean surroundings and most be performed in an enclosed area.
  By default it is indicated where the process is physically located, i.e. in the position in a specific production facility or at another production sites.

Figure 6.19. shows an example of how the processing steps are modelled in the supply chain analysis.

Input materials enter the process in the top to the left and transformed output materials exits in the bottom to the right.

The process name defines the class to which the specific process belongs. In the upper left corner is a process identification number. This number is used for unambiguous identification of the processing step. This number is useful when referring to a specific processing step, as multiple processing steps carry identical names since they belong to the same class and perform similar transformations – although in distinct ways.

The colouring of the box indicates the type of process, i.e. purchasing, fabrication, assembly, or testing, which can be considered as high level super classes.

Below the process name is a description of the purpose of the class or process, i.e. a description of the transformation that happens during the process. The description is written in grey font.

This is followed by attributes that describe the operators (TS, Hu, and En), which carry out the process. In figure 6.19. three attributes (technology, automation, and location) is used to describe the technical, human, and environmental system, respectively. As discussed earlier, further attributes can be included if it is considered to be relevant. Attributes describing the process operators is written in blue.

In order for two parts to be output from the same process it is required that the parts belong to the same class according to the PFMP. If this is not the case, the processes can consequently not belong o the same class of processes. When all output materials from a process step belong to the same class it is easier link the processing step to the PFMP. The output class (crankset) is indicated in black text below the description of the process and the operators.

In the bottom of the modelled process step is a list of all output materials that are the resulting outcome of this specific process step. Each output item is identified by a code number plus a description of what the part is (For easier navigation an illustration describing the process can be included with advantage.

the description in the ERP system is often not identical to the class name). Further information about the output materials (e.g. the volume that exits this process) can be added as it is considered relevant.

From each listed output material is drawn an arrow that indicate the subsequent flow of materials and show which processes the materials serve as input to. The arrows can converge and/or diverge as necessary to describe the flow of materials. Above these arrows is an illustration which indicates the output class and makes it easier to navigate the supply chain model and link it to the PFMP.

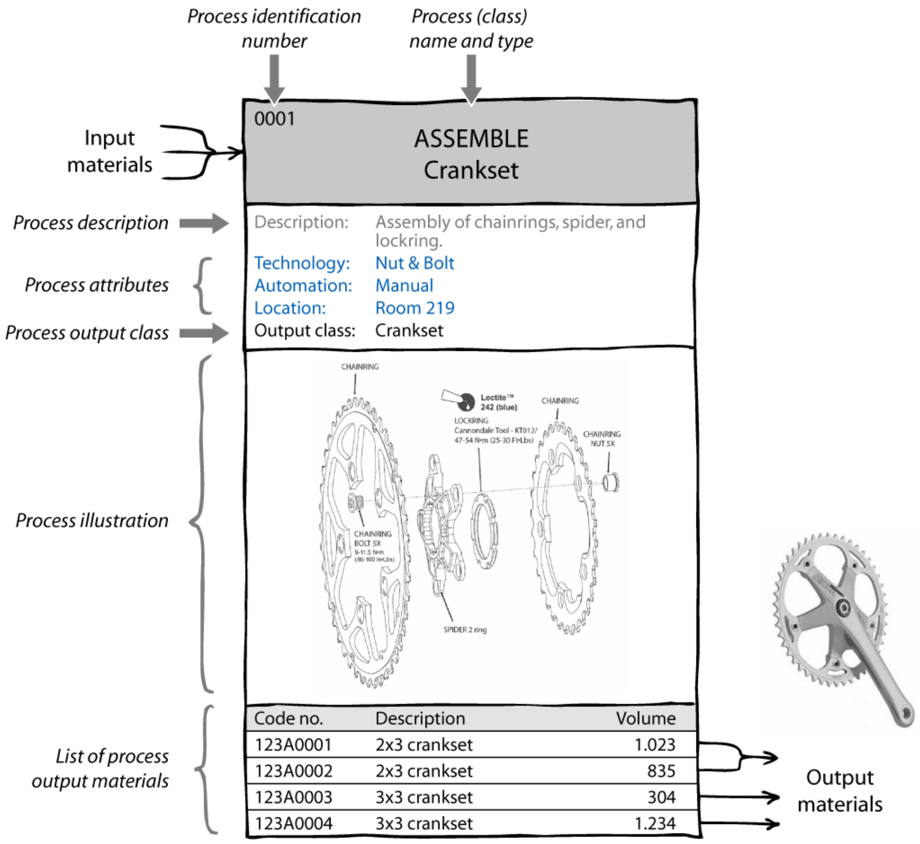

Figure 6.19. *Modelling the processing steps. Input materials enter top left and output materials exit bottom right. The modelling element includes a unambiguous identification number, a process name, a process description, attributes describing the process operators, identification of the output class, a illustration of the transformation that occurs, and finally, a list of all output materials.*

In the following sections is described further how the modelling formalism is adapted to better suit the different types of processing steps (purchasing, fabrication, assembly, and testing) which has the focus in this research work.

Purchase process modelling

Figure 6.20. illustrates an example of the modelling of a purchasing processing step.

First and foremost it is somewhat an exaggeration to denote the purchase of materials as a technical process as no actual input (material, energy, or information) is transformed into another more beneficial output state. Instead, the input (money) is exchanged for a different output – in this case ‘aluminium rod’. Consequently, purchasing steps are modelled without any input materials. If we were to track the flow of materials further backwards, we should study how aluminium ore is transformed into aluminium rods, but this is of no relevance for the design of the products. In this way the purchasing process steps indicate the entry point of the supply chain that is to be modelled, i.e. where materials enter.

Two attributes that are of high relevance in relation to re-design and rationalisation is the identity of the supplier and the location of the supplier, as the number of different supplier and the proximity of those has impact on the fixed and variable costs.

Typical additional information that can be relevant to connect to the output materials is the cost price, which can be used for comparison between suppliers.

Since, no real transformation occurs it is irrelevant to include an illustration of the process.

0001

PURCHASE
Aluminium rod

Description:	Procurement of aluminium rods
Supplier:	Aluminium Inc.
Location:	Bergen, Norway
Output class:	Aluminium rod

Code no.	Description	Price [$/m]
123A0001	Ø20 mm. Al. rod	61,32
123A0002	Aluminium rod ø25	87,13
123A0003	Rod aluminium 30mm.	108,43
123A0004	Aluminium ø35 mm	127,75

Output materials

Figure 6.20. *Modelling purchasing process steps Purchasing. Purchasing steps has no input materials or illustration as no real transformation of materials occurs during the process.*

Fabrication process modelling

In figure 6.21. is shown an example of fabrication process modelling.

0002

FABRICATE
Gear wheel

Description:	Aluminium rod is transformed into gear wheel.
Technology:	CNC milling
Machine:	Haas EC-400PPHE
Automation:	Semi-automated
Location:	Hall C - 2D
Output class:	Gear wheel

Code no.	Description	Volume
123A0005	Chainring - 52	1.345
123A0006	44 gear	1.235
123A0007	48 gear wheel	409
123A0008	Gear wheel 36	1.864

Figure 6.21. *Modelling fabrication process steps. Typically, raw materials are transformed into parts or semi-manufactures.*

Fabrication processes typically transforms raw materials (input) into e.g. machined parts (output).

In relation to fabrication processes it is typically relevant to indicate the used process technology (and the specific machine) as the technology often set great demands to the design of the products – either because the process has certain limitation or because certain requirements must be fulfilled in order for the process to work properly. In this way variety in the choice of technology can entail variety in the products, i.e. necessary variety that is needed in order to utilise different process technologies.

Also, it is relevant to indicate what level of manual resources – in terms of quantity and competencies - that is required in the process (i.e. the level of automation) as the manual labour is normally a major cost driver.

Finally, it is a good idea to indicate the location where the process occurs. This makes it possible to link the flow of materials in the supply chain (remember this in modelled from a time perspective) to a factory layout drawing, a world map, etc.

For a fabrication process it can be relevant to link many different pieces of information to the output materials. In figure 6.21. the volume that is fabricated is indicated, but data such as processing time, process costs, typical batch size, changeover time, etc could also be relevant.

Assembly process modelling

Figure 6.22. includes an example of assembly process modelling.

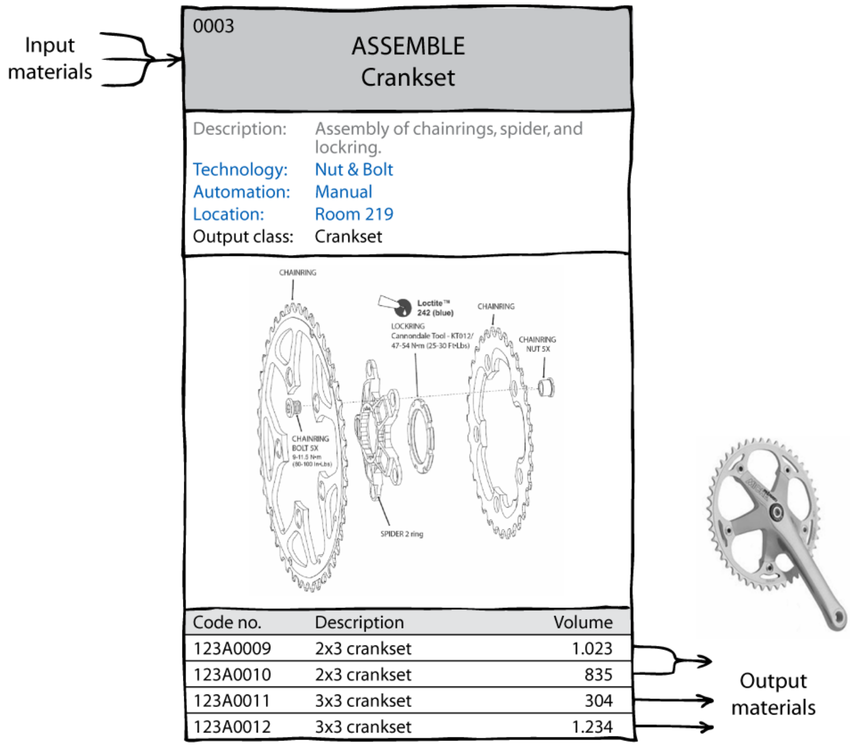

Figure 6.22. *Modelling assembly process steps. A number of input materials are joined together.*

Modelling assembly process steps is very similar to modelling fabrication steps. The main difference is that assembly processes typically has input from various product element classes which are to be joined in the process, whereas, normally only one class of material enter a fabrication process. This has no actual consequences for the modelling technique.

Concerning attributes that are relevant in order to describe the process operators it is similar as to the attributes considered relevant to the fabrication processes, i.e. technology, machine, level of automation, location, etc.

Exploded views of the assembly are usually a good way to illustrate the assembly process step.

Testing process modelling

Figure 6.23. presents an example of testing process modelling.

From a material perspective it is difficult to argue that testing processes should be considered to be technical processes as same material enter and exit the process without any transformation of the material have occurred, i.e. material input and output is identical. From an information point of view it is somewhat different, as the main output (the test result) is information generated and consequently transformed during the process. Basically, the outputs of testing processes are materials of different quality grades – often simply as *approved* or *scrap*.

This might suggest that testing processes not are relevant as the focus in on modelling the flow of materials - not information. But, just like the operators of fabrication and assembly processes can have influence on the product design – and vice versa – the operators of a testing process and the product design can entail constraint on one another.

Two attributes, which are especially relevant to testing processes, describe the test object (i.e. what are we testing for?) and the test method. The test method is somewhat comparable to the 'technology' attribute used to describe the fabrication and assembly processes.

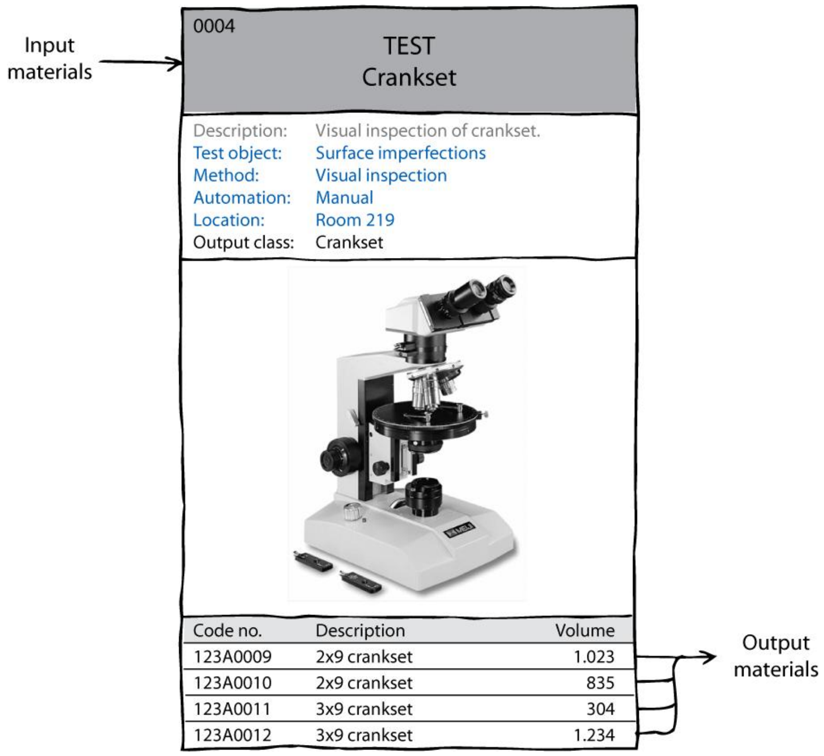

Figure 6.23. *Modelling testing process steps. Parts or assemblies are tested. Input and output materials are basically the same as they are not transformed in the test process.*

6.4.4. Conclusion on the supply chain analysis

The supply chain analysis modelling formalism presented in the previous sections contribute to the research by addressing three of the requirements set to the tool in section '4.3. Requirements':

Production/supply chain system

The processing steps in the supply chain are modelled based on the theory of technical systems and technical process modelling.

As described in section '4.3.7. Supply chain system' the objectives behind modelling of the supply chain are threefold: (a) it should support visualisation of variety within the supply chain (i.e. variety of processes), (b) it should support identification of life phase system relations, and (c) it should enable identification of the point of variegation.

As to the last two objectives they will be accounted for in the subsequent sections.

Concerning the visualisation of variety this is achieved through the use of classes and coherent attributes similar to the way product variety is modelled in the part-of and kind-of structures of the PFMP, i.e. based on system and object-oriented modelling.

Point of variegation

Because the supply chain analysis focus on modelling the flow of materials it is relatively easy to identify the processing steps where variety is introduced (i.e. the point of variegation), as the relationship between input materials and output materials indicate the level of variety that is introduced during the process.

Life phase system relations

Linking the supply chain to the structure of the products is a prerequisite to identify life phase system relations. The supply chain analysis enables linking to the PFMP (i.e. the product structure) by indicating to each process is the outcome material using the classification which has been defined in the PFMP. This gives an understanding of what role each process play in the value creation process.

Furthermore, the unambiguous numbering of the processing steps in the supply chain analysis makes it possible to indication in the PFMP. In this way it is relatively easy to track where, when, and how each part/assembly emerge in the supply chain.

6.5. Overview of the total product offering

As it was discussed in section '4.3.2. Value of variety' a specific product variant, feature, etc. can add value to the business in many ways. When re-designing a product family it is critical to understand what role the different elements in the product family play in the company's pursuit of success.

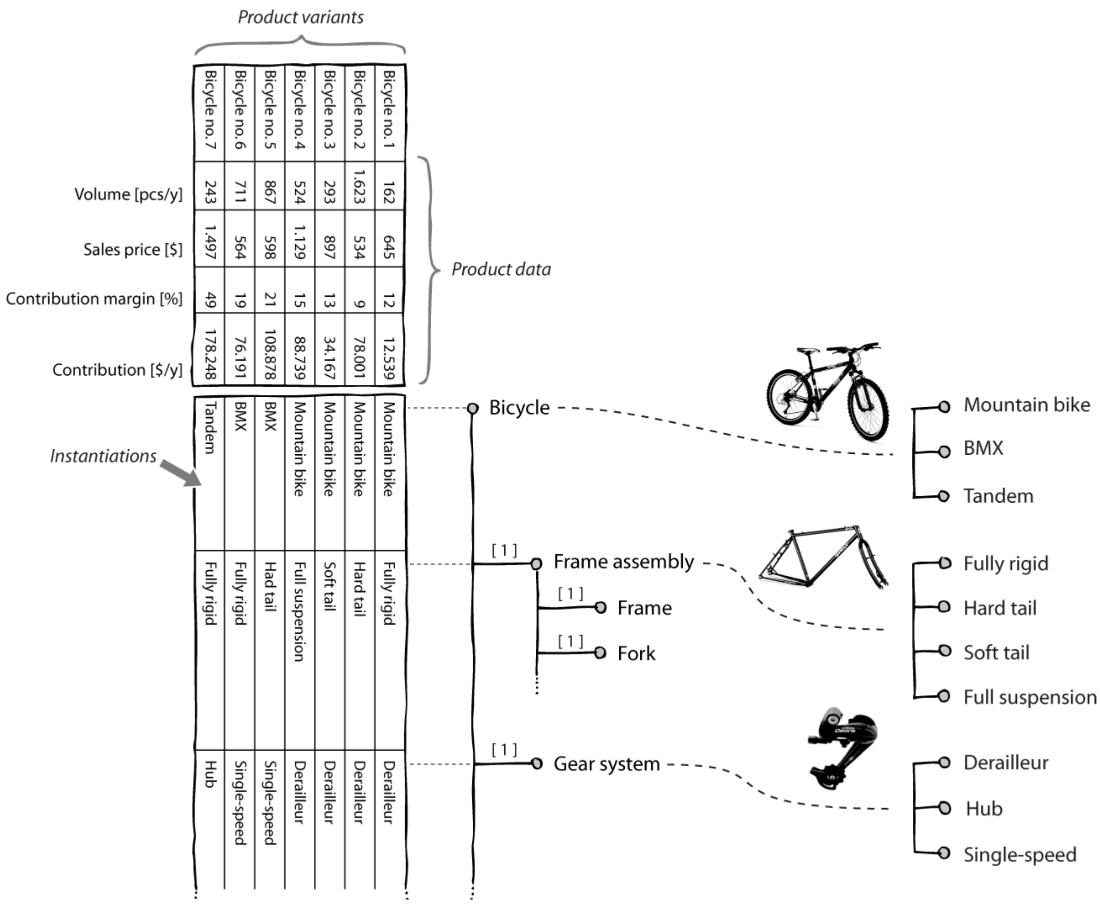

Figure 6.24. *A matrix links via the product variants in the product family relevant product data from the ERP system (or similar) to the element s in the PFMP, i.e. features in the customer view, organs in the engineering view, and parts/assemblies in the part view.*

The main objective of presenting an overview of the product offering is to support strategic prioritising of the various product features, organs, and components in the product family in connection to a re-design process. Accordingly, the model should present to what extend each element in the product family contribute to the business.

Evidently, it is of interest to understand which product variants are profitable and which are not. Such information is typically readily available in the company's ERP system and something the employees in the company are already more or less conscious about, though, maybe not in details.

The modelling formalism presented in this section provides a technique which can be used to illustrate the importance of the different product features, organs, parts/assemblies, etc. regarding different aspects of the business.

Typically, product data such as sales volume, sales price, contribution margin, etc. are linked to the specific product variants in the company's various data systems. When utilising the classification provided by the PFMP it is possible to link this product data to the various features, organs, parts, assemblies, etc. in the product family.

Such an analysis is typically referred to as data warehousing [Inmon, 2002]. A data warehouse provides a common data model for all data of interest, regardless of the data's source. This makes it easier to report and analyse information than it would be if multiple data models from disparate sources were used to retrieve information such as sales invoices, order receipts, general ledger charges, etc. [Yang, 1998].

Figure 6.24. illustrates how the product data is linked to the elements in the PFMP. Above to the left of the part-of structure in the PFMP a matrix lists all product variants included in the analysis horizontally and the relevant/available product data from the ERP system vertically. Below the matrix it is indicated for each product variant the instantiations of classes in the customer, engineering and part view that constitute the specific product variant, i.e. a configuration list that describe what the product does (customer features), how the product works (organs, and how the product is build (parts and assemblies).

Now that instantiations all products in the analysis have been unambiguously classified and the classification are linked to product data from other systems it is possible to extract information about how sales volume, turnover, contribution, etc. is distributed across the variety of features in the customer view, organs in the engineering view, and parts/assemblies in the part view (fig. 6.25.).

Presenting multiple charts on distribution across variety gives a more balanced picture. The number of tandem bicycles sold for instance only represents a small fraction of the total volume but still the bigger contribution margin means that the tandem bicycles contribute just as much to the overall business as mountain bike and BMX bicycles.

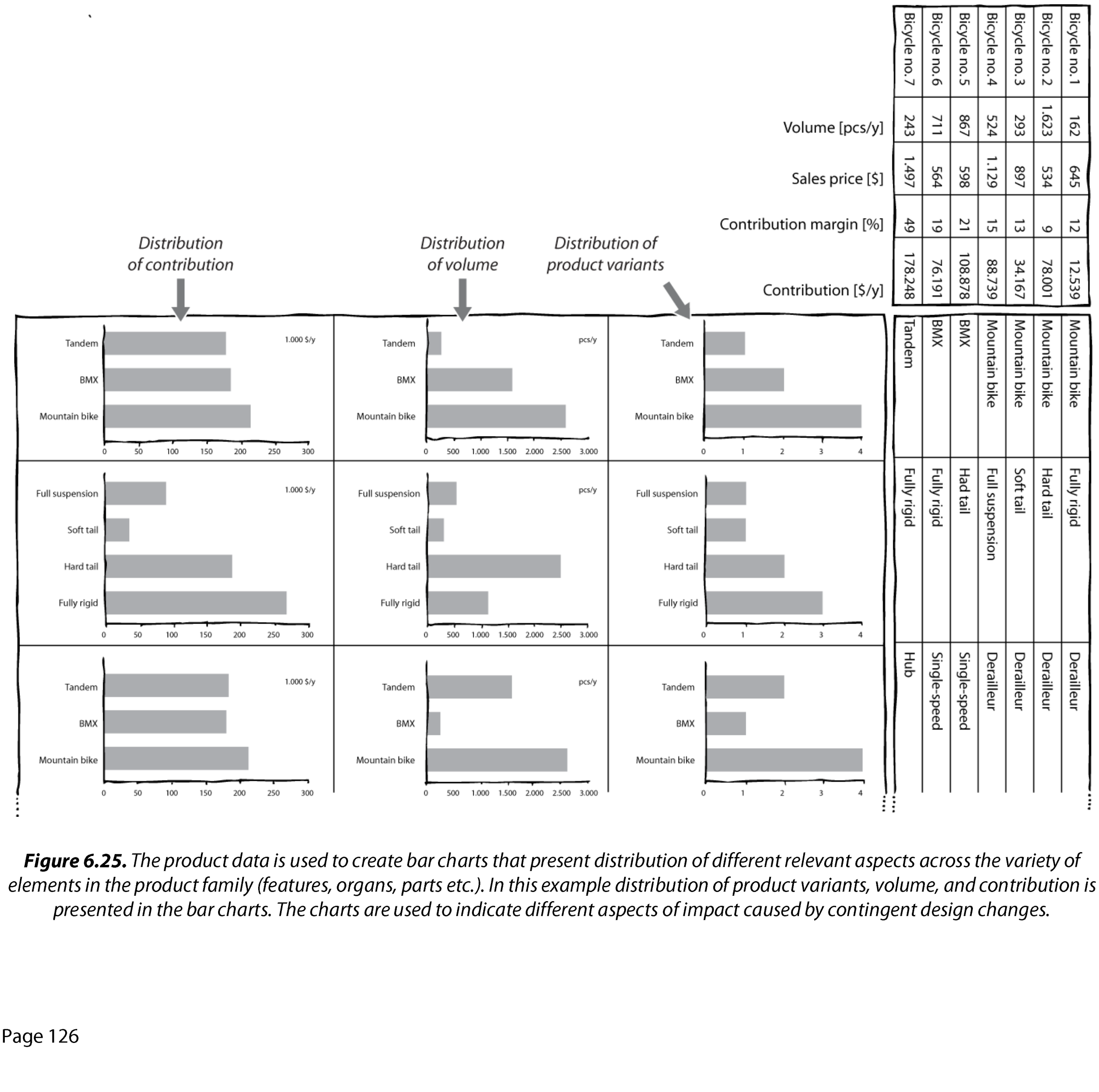

Figure 6.25. *The product data is used to create bar charts that present distribution of different relevant aspects across the variety of elements in the product family (features, organs, parts etc.). In this example distribution of product variants, volume, and contribution is presented in the bar charts. The charts are used to indicate different aspects of impact caused by contingent design changes.*

The bar charts in figure 6.25. can be used to indicated the importance of features, organs and parts/assemblies and thus prioritise between them when re-designing the product family – similar to the pareto analyses proposed by Anderson & Pine [1998].

What charts is included in the model is dependent on what product data that is available. The charts presented in figure 6.25. are relevant in relation to the re-design process because they represent different aspect of impact caused by design changes:

- *Distribution of product variants*
  Distribution of product variants is relevant because it indicates how many product designs are influenced by the design change.
- *Distribution of volume*
  Distribution of volume is relevant because it indicates the potential of making a design changes – even small changes on a large volume can have great positive impact on the total business and vice versa.
- *Distribution of contribution*
  Distribution of contribution is relevant because it indicates how importance to the business. That is, to what extend a specific element (feature, organ, or part/assembly) contributes to the business, i.e. adds value to the business.

A final element that is included in the model is the opportunity to explicitly indicate other reasons (than evident profitability) why a product variant is important to the business (fig. 6.26.).

	Bicycle no.7	Bicycle no.6	Bicycle no.5	Bicycle no.4	Bicycle no.3	Bicycle no.2	Bicycle no.1
Strategic importance	2				1		
Volume [pcs/y]	243	711	867	524	293	1.623	162
Sales price [$]	1.497	564	598	1.129	897	534	645
Contribution margin [%]	49	19	21	15	13	9	12
Contribution [$/y]	178.248	76.191	108.878	88.739	34.167	78.001	12.539

Strategic importance

Figure 6.26. *If a specific product variant is strategically important for other reasons than evident contribution to the company's profit, then it can be indicated in the matrix. Unambiguous numbering is used for the purpose of referring to an explanation of why the specific product variant is considered as strategically important.*

Again, these identifiers of strategic importance are given unique numbers. These numbers then refer to a more thorough description of why the specific product variant is considered as strategically important.

A specific product could for instance be considered as strategically important because it is sold to a significant customer as part of larger business agreement, which entails valuable sales of other product variants that would not be obtainable without having the relevant product variant available to the customer. Then the number would then refer to a text explaining that this product variant is strategically important because it is included as a part of this specific business agreement.

6.5.1. Conclusion on the overview of total product offering

The modelling element denoted as 'Overview of the total product offering' which is presented in this section meet the demands that have been put on this research work (see section '4.3. Requirements') in a number of ways:

Value of variety

The modelling technique presented here enables linking of product data from the company's ERP system and thereby present views on how the variety of features, organs, parts/assemblies add value to the business.

The bar charts can be used to indicate how each element contributes to the business, i.e. evaluate the value of the variety. As a rule thumb the contribution of a specific element is measured by the scores in the bar charts. High score in multiple charts indicate that the specific features contribute relatively much to the business.

Consider the derailleur gear system in figure 6.25. It scores relatively high in all three aspects, i.e. many product variants have a derailleur gear system, a relatively large part of the total volume of bicycles sold has a derailleur gear system, and finally a relatively large proportion of the total contribution is derived from bicycles having a derailleur gear system. Consequently, the derailleur gear system contributes and adds value to the business.

The soft tail suspension system (frame assembly) on the other hand is only used in a single product variant (bicycle no. 3), which is only sold in a relatively low volume and consequently only produce a fraction of the compiled contribution (fig. 6.25.). In such a case it is relevant to question whether or not the specific feature, organ, or part/assembly (soft tail suspension system) could be substituted by one of the alternative variants (fully rigid, hard tail, full suspension). In this case, however, the product variant (bicycle no. 3) is marked as being a strategically important variant (fig. 6.26.). The reason could for example be that it is a new product pointed at a market segment that is expected to grow rapidly in the nearest future.

Similar analysis can be conducted using out-of-the-box data warehousing systems (e.g. SAP's Business Information Warehouse) but this would require a classification of the elements in the product family similar to the classification made in the PFMP.

One of the strength of the presented model is that it links the product data directly to the product structure as it is defined in the PFMP part-of structure and is therefore not depend on how the product structure is defined in for instance the ERP system. Reuse of the same product structure enables easier navigation among the information presented in the 'overview of total product offering', simply because it is presented in a joint model and because of the one-to-one mapping between the classes in the PFMP structure and the presented bar charts (fig. 6.25.).

Strategic importance

The model enables explicit identification and retention of strategically important product variants and also to explain why the variant is considered as strategically important.

The fact that the identifications are made explicitly means that someone within the company must take the responsibility for the nomination and furthermore the nomination must be backed up by argumentation for the strategic importance. Thus, random and ill-founded declaration of untouchable products, features, etc. that impede decision-making can be limited to a minimum.

Customer perceived product offering

Though, the customer view in the PFMP should describe the product family seen from the customer's point of view it does not facilitate weighting of the variety of features. The customer view might reveal that the customer can choose between three options but it does not indicate the anticipated distribution of the variety, i.e. how many customers prefer option 1, 2, and 3, respectively?

The bar charts included in this model illustrate the distribution of customers among the variety within the product offering.

6.6. Overview of critical design issues

The main purpose for modelling the overview of critical design issues is to capture information about design issues that should be avoided and forward this information to the design team that is responsible for the re-design of the product family.

Hence, the overview of past and current critical design issues is basically a notice-board where engineering designers, production technicians, marketing, etc. can call attention to design issues that they have encountered in their work.

Figure 6.27. illustrates how the design issues are posted around a schematic drawing of a "typical" product, i.e. an ordinary bicycle.

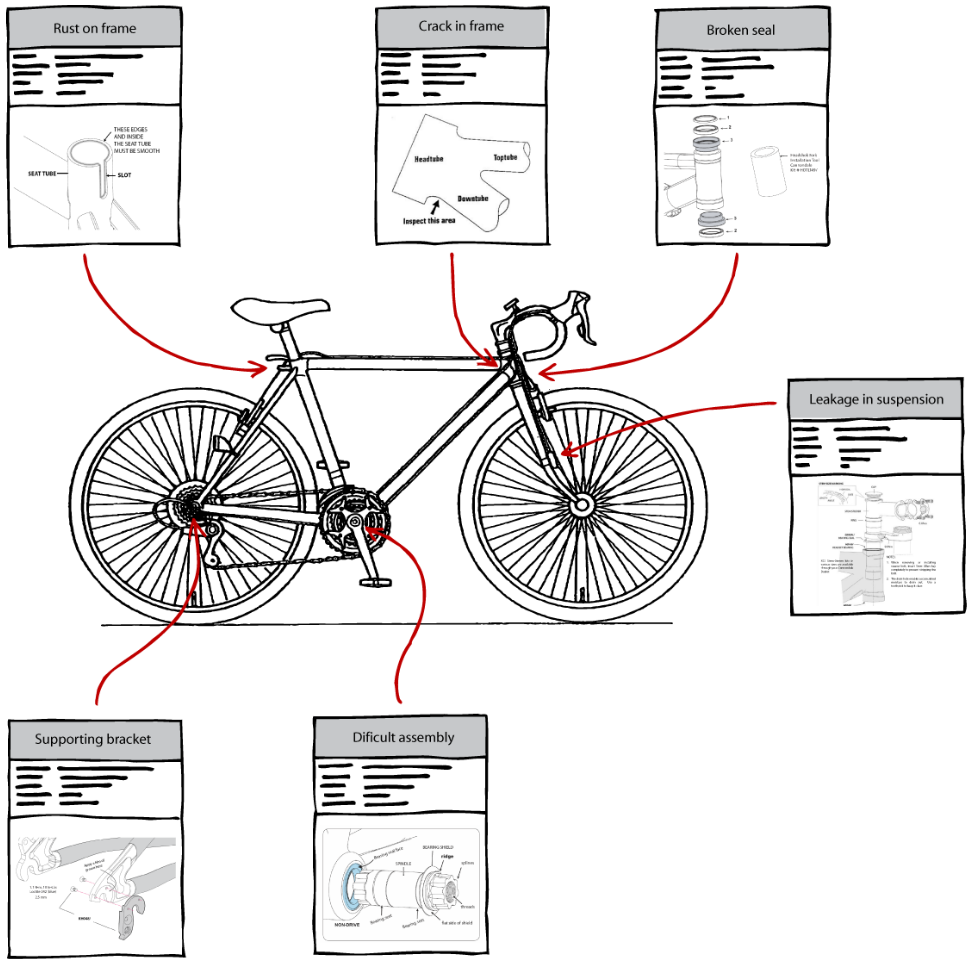

Figure 6.27. *Overview of critical design issues. A generic model that represent the product serves as a notice-board where designers, production technicians, marketing, etc. can post design issues that they have encountered in their work.*

The modelling formalism is not considered to be of critical importance but still some elements are recommended to be included in the model. In figure 6.28. is illustrated an example of the elements that should be included when describing such a design issue.

The description mode for critical design issues is built up in a similar way to the description model used to model processing steps in the supply chain.

In the upper left corner is a unique identification number which is useful for reference purposes. The top box also includes a design issue name.

Below is a verbal description of the design issue which together with the illustration explains the problem and is possible the reason that causes the problem.

Furthermore, the description should include a reference to either a person/expert (e.g. the one who posted the specific design issue) or to other documentation (e.g. a design report, test results, etc.) that describes the problem in detail.

The description also includes an indication of what class of product elements that is affected by the design issue (i.e. feature, organ, part or assembly). This enables easy reference to the product structure as described in the PFMP.

Finally, a list of the specific parts/assemblies can be included in the bottom of the model when it is relevant and possible to link the design issue to the specific physical elements.

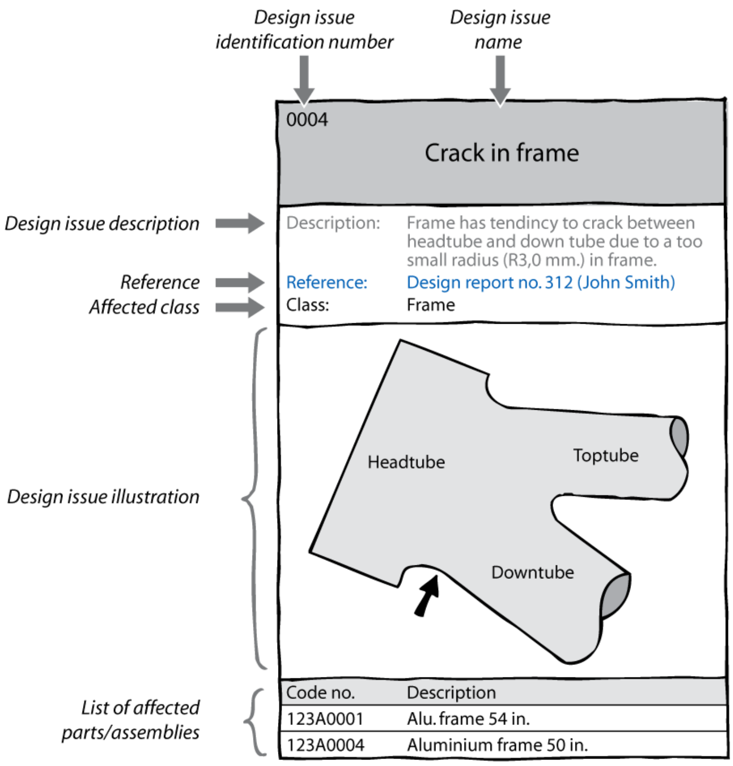

Figure 6.28. *Modelling critical design issues. The modelling element includes an unambiguous identification number, a design issue name, a description of the design issue, references to other documentation, identification of the affiliated class of elements, a illustration of the problem that occurs, and finally, a list of materials that are affected.*

6.6.1. Conclusion on the overview of critical design issues

The modelling element denoted as 'Overview of critical design issues' which is presented in this section is basically an attempt to meet the requirement described in '4.3.9. Critical design issues':

Critical design issues

By bringing information about encountered design issues forward and presenting it visually to the design team should help to prevent that these felicitous designs are copied in the process of re-designing the product family.

Simply having the opportunity to post design issues, causes that the people in the organisation begin to reflect whether or not they possess any critical information that should be communicated to the design team.

The relatively loose modelling formalism provides a simple way of handling most design issues - whether it is things that should be avoided in the future design or it is details of a design that is critical for the functionality of the product.

6.7. Coherence between the modelling elements

As the main focus of this research is on life phase relations between the product design and especially the supply chain it is of critical importance that the different modelling elements described in the above sections are linked to each other.

In this section is described a number of initiatives that should facilitate navigation among the modelling elements and consequently support identification of life phase relations.

As it is described in section '6.5. Overview of the total product offering' the modelling element denoted by the same name, can be considered as an add-on element to the PFMP modelling element and they are therefore naturally linked together. How they link together has already been described in the coherent section. Consequently, this section will focus on coherence between the PFMP, the supply chain analysis, and the overview of critical design issues.

Relations among these modelling elements are primarily made visible in two different ways:

- Use of cross references
- Definition of sub product families

The two alternatives are described in the following sections.

6.7.1. Use of cross references

Figure 6.29. illustrates how the elements in the PFMP, processes in the supply chain, and design issues can be linked together by the use of unique identification numbers in the supply chain analysis and in the overview critical design issues, respectively, plus unambiguous class names in the PFMP.

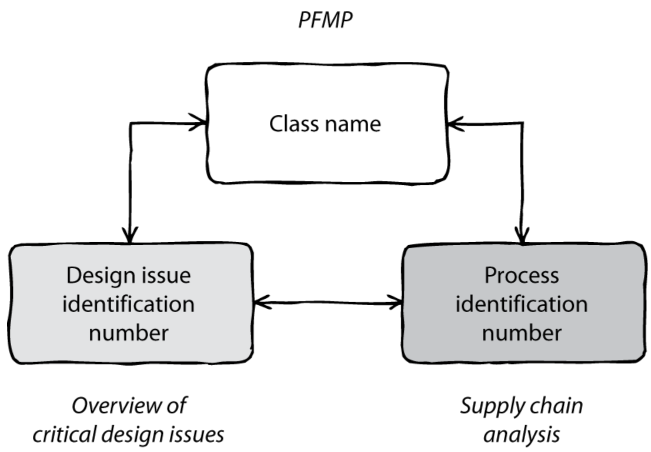

Figure 6.29. *Unambiguous identification through the use of class names (PFMP), process identification numbers (Supply chain analysis) and design issue identification numbers (Overview of critical design issues) enables cross referencing among the different modelling views.*

Figure 6.30. illustrates how cross references from any class in the PFMP – in the part-of structure or kind-of structure – are made to process steps in the supply chain or design issues, respectively.

In green font is described where this class of elements appear in the supply chain, i.e. where are they purchased, fabricated, assembled, and tested. The example in figure 6.30. indicates that the class of frames originate from two different processes in the supply chain. This can be caused by many things. When the class include multiple elements maybe some elements are purchased as finished parts/assemblies, others are maybe fabricated or assembled in the factory. Anyway, when more than one process step is indicated one should consider the reasoning behind, as this is possibly nothing but unnecessary variety of processes.

Below (in orange) are indicated contingent design issues that have been encountered in this class of elements. Again, multiple design issues are a possibility and if so the new design should probably be contemplated thoroughly in order to prevent recurrences.

Similar cross referencing is made from processing steps and design issues to elements in the PFMP as described in section '6.4.3. Modelling the processing steps' and '6.6. Overview of critical design issues', respectively.

Likewise it is possible to make references between processing steps and design issues if necessary. It is very plausible that a design issue could be caused by process step, which the company does not fully control. Such references are made similar to referring to elements in the PFMP using identification numbers (for process or design issues) instead of class names.

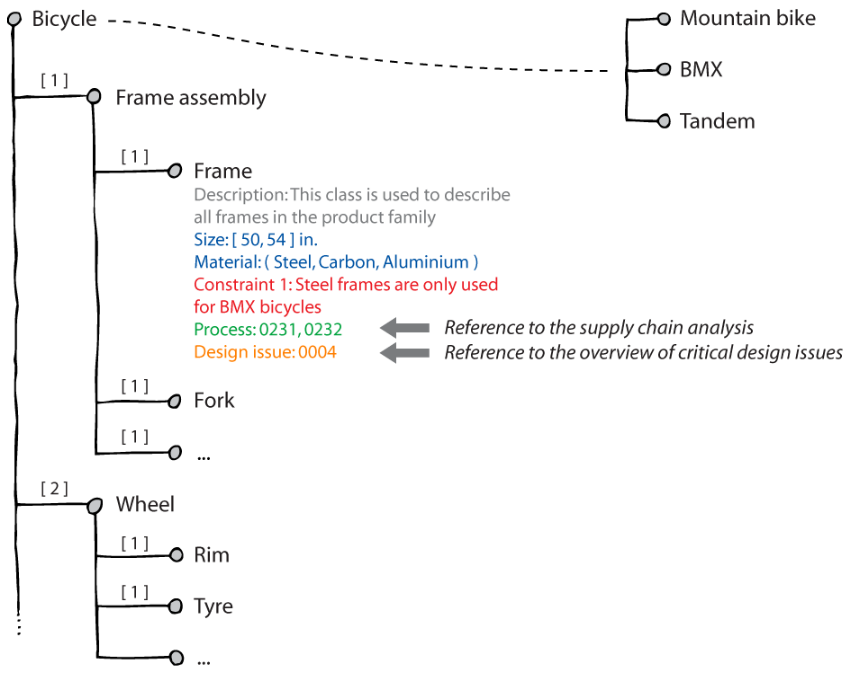

Figure 6.30. *In the PFMP classes in the part-of and kind-of structure can refer to process steps in the supply chain analysis and if relevant to posted design issues using the respective identification numbers.*

6.7.2. Definition of sub product families

The objective behind sub categorising the product family into sub product families is to enable a more visual linking of the modelling elements. The intention is to use coding of the sub product families, i.e. give each sub product family a colour and mark elements in the various modelling views that are related to the specific sub product family. That is all product features, organs, parts and assemblies that are part of the sub product family are marked in the PFMP, all process steps that are necessary to derive the products in the sub product family are marked in the supply chain analysis, etc.

As the definition of sub product families is merely a means to visually map relations between the modelling elements, it not of great importance how the sub product families are defined. In order to make the colour-coding work properly it necessary to limit the number of sub product families as it can be difficult to find enough colours that are easily distinguishable, i.e. dependent on software, printer, etc. a maximum of 10-15 sub product families is recommended – and preferably less. However, completely random subdivision of the product family is not desirable, as this will only add to the confusion.

An unlimited number of classifications can be used for sub division of the product family and no single method can be declared as the right one. The products could for instance be categorised by price level, markets and/or regions, performance, colour, etc.

As mentioned earlier in relation to value stream mapping (section '6.4. Supply chain analysis') product families are defined by the processing steps that are necessary in order to produce the products, i.e. products that pass through the same processing steps belong to the same product family. This is another way to sub divide the products.

In the case of the bicycle product family it is chosen to categorise the bicycles according to the type of bicycle. That is, all mountain bikes belong to the sub product family A, all BMX bicycles to sub product family B and so on.

In the following is presented the formalism used in each modelling element to denote the sub product families.

PFMP

In the PFMP the elements affiliation to sub product families is marked by substituting the black dot that denote the class with a number of coloured dots according to the class' affiliation to different sub product families. This is illustrated in figure 6.31.

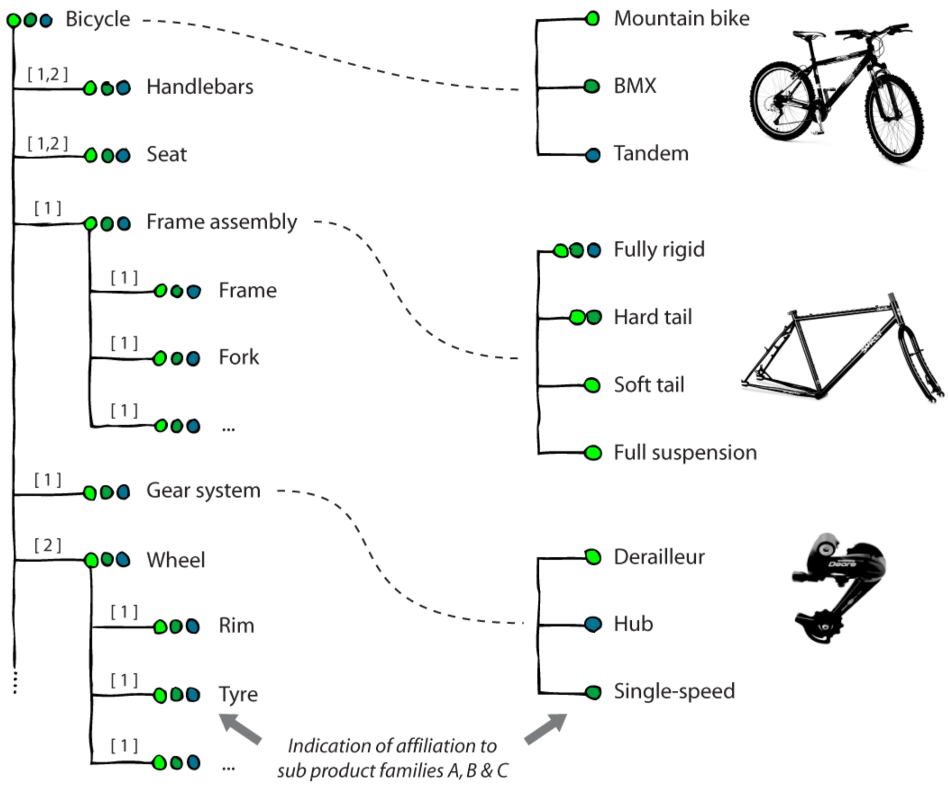

Figure 6.31. *A class' affiliation to a sub product family is indicated by replacing the black dot next to the class name with coloured dots that represent the respective sub product families.*

Note that the labelling is done in the part-of as well as the kind-of structure. In this example the part-of structure is identical for all sub product families and only the kind-of structures vary.

Supply chain analysis

In the supply chain analysis it is relevant to indicate the processing steps' affiliation to the sub product families (i.e. an overview of what process steps is needed to produce the products in each sub product family) as well as indicating the flow of materials' affiliation to the sub product families.

Figure 6.32. illustrates how relations to sub product families are indicated for processes and output materials, respectively.

In the topmost box, which include the process name and identification number coloured bars to the right indicate that the process steps is part of the supply chain for the respective sub product families (red= mountain bike, pink= BMX, blue= tandem).

Likewise, in the bottom most right corner coloured bars opposite the list of output materials indicate each material's affiliation to the various sub product families.

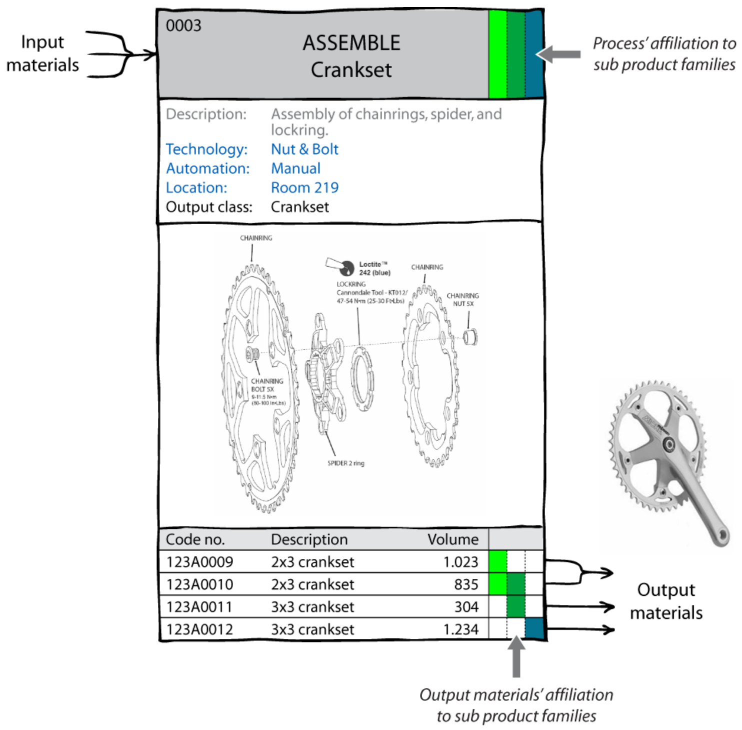

Figure 6.32. *A process steps' affiliation to a sub product family is indicate by coloured bars in the top right corner. Likewise, coloured bars in the lower right corner indicate the output materials affiliation to sub product families.*

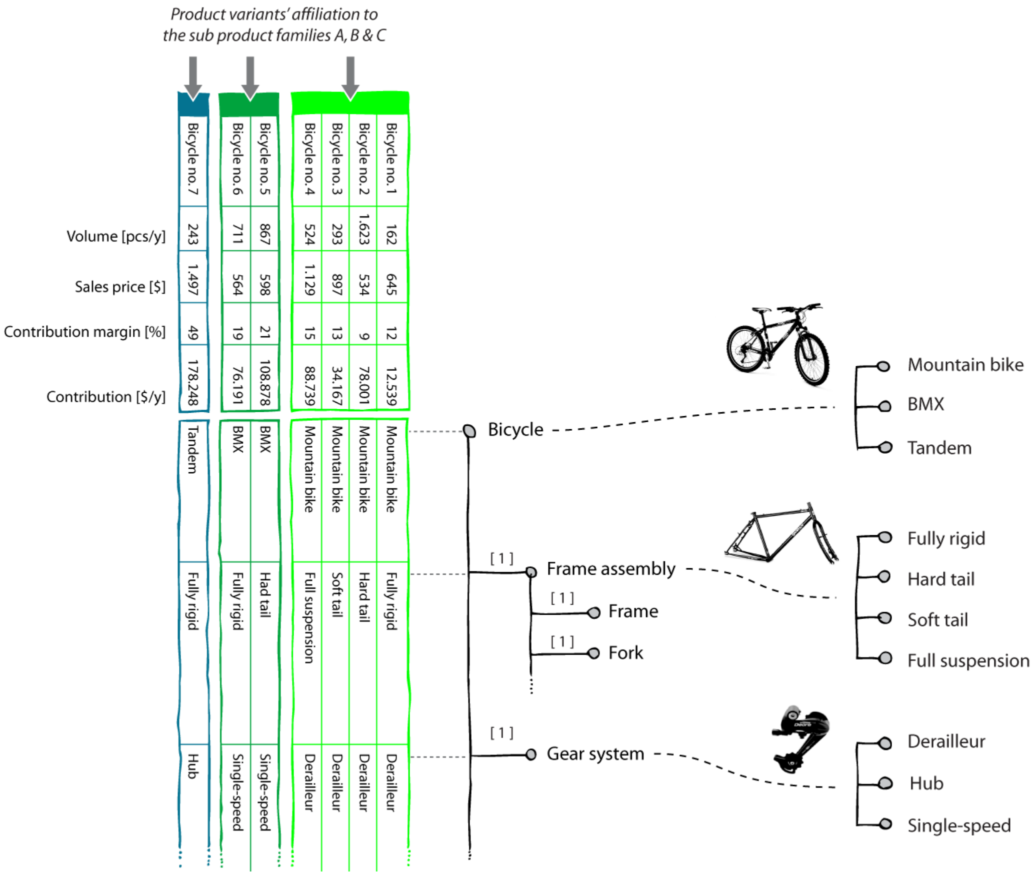

Figure 6.33. *In the overview of the total product offering the product variants are arranged in coloured tables according to their affiliation to the respective sub product families.*

Overview of the total product offering

In the overview of the total product offering indication of the sub product families is straightforward. The product variants are simply arranged in separate tables according to which sub product family they belong. The colour of the tables indicates what sub product family the product variants belong to. The example in figure 6.33. illustrates how all mountain bikes are arranged in a separate *red* table, the BMX bicycles in a *pink*, and the tandem in a *blue* table.

Overview of critical design issues

Critical design issues' relationship to the different sub product families are indicated identically to the way it is done for processes in the supply chain analysis. This is illustrated in figure 6.34.

Coloured bars indicated the design issues affiliation to the sub product families in the topmost right corner and similarly, coloured bars show the specific affected materials affiliation in the bottommost right corner opposite the list of the materials that are affected by the design issue.

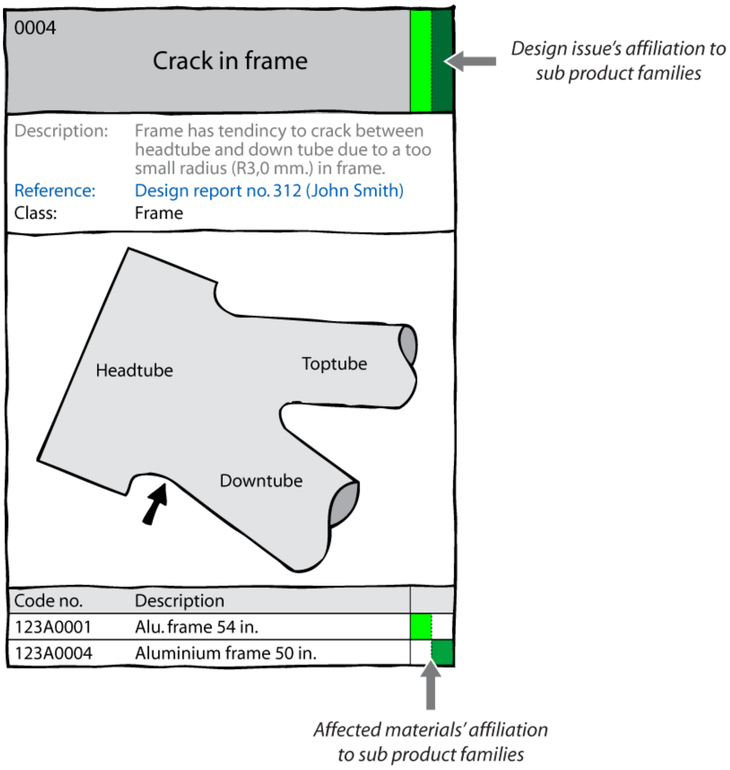

Figure 6.34. *Design issues' affiliation to sub product families is indicated in the top right corner. Affected materials' affiliation is similarly indicated by coloured bars in the lower right corner.*

6.7.3. Conclusion on coherences between the modelling elements

The purpose of accentuating coherences between the modelling elements is primarily to accommodate the requirement described in the section '4.3.5. Life phase system relations'.

Life phase system relations

The use of cross references and colour-coding of sub product families tie the different modelling elements together and enables easier navigation through the information that is presented in the different modelling views. As a consequence relations - including life phase system relations – become more apparent and easier to identify when analysing the product family.

Linking the modelling views together in this way makes it possible to investigate how the processing steps in the supply chain contribute to the business.

Not that cross referencing and colour-coding alone disclose desirable and inappropriate dispositions made when the products were designed, but it helps raising questions that led to a better understanding of the life phase system relation and identification of potential waste. For instance, "why do we have separate processing steps marked 'assemble FRAME' for each sub product family?"

Also, especially the colour-coding is a powerful way to indicate how much would be affected if a certain part, assembly, organ or feature were to be changed or removed. This is naturally relevant in relation to re-design of a product family.

6.8. Conclusion on the PFMP^2 tool

In the above sections it has been accounted for how and to what extend the different elements in the developed PFMP^2 tool accommodate the requirements that were put up and described in section '4.3. Requirements'.

Consequently, it is only left to conclude on how the requirement set to the format of the tool is accommodated by the PFMP^2 tool.

Format of the tool

- The generous use of illustrations in all modelling elements of the PFMP^2 tool enables easy navigation among the information, as the observer due to the graphical representations can take two steps back, get an overview, orientate and locate where the sought information can be found. Then step closer and study the details.
- Furthermore, the cross references and the colour-coding of sub product families together with the rich use of graphical representation tie the otherwise scattered pieces of information together. In this way the PFMP^2 tool facilitate to link the pieces of information into a context.

Part 7

Product family assessment at Danfoss Automatic Controls

This part reports the experience from applying the research in an industrial case. The tool has been used to analyse a product family of solenoid valves at the company Danfoss AC. The results of the analysis have been the initiation of the largest product development project in the history of that particular business unit. The project has been running for four years and constitutes a significant part of the annual turnover regarding the product scope. The work in this thesis was used to initiate the industrial project.

7.1. Background

7.1.1. The Danfoss Group

The Danfoss Group is the largest Danish industrial manufacturer. Danfoss produces and sells mainly mechanical and electrical components to a broad variety of industrial applications. Danfoss operates in the business-to-business markets, meaning that Danfoss' customers are not the end-users. Instead, Danfoss' customers are either wholesalers or so-called *original equipment manufacturers* (OEM) who install Danfoss components in their applications.

Danfoss is the leader in several markets and have the reputation of being among the first-movers when it comes to adopting new technologies and developing products. Furthermore, Danfoss is known to supply high-quality products and provide qualified technical assistance when needed.

Danfoss business divisions and units

The Danfoss Group is organisationally divided into three autonomous business divisions, which then are sub-divided into multiple business units. The organisational structure of the Danfoss Group is illustrated in figure 7.1.

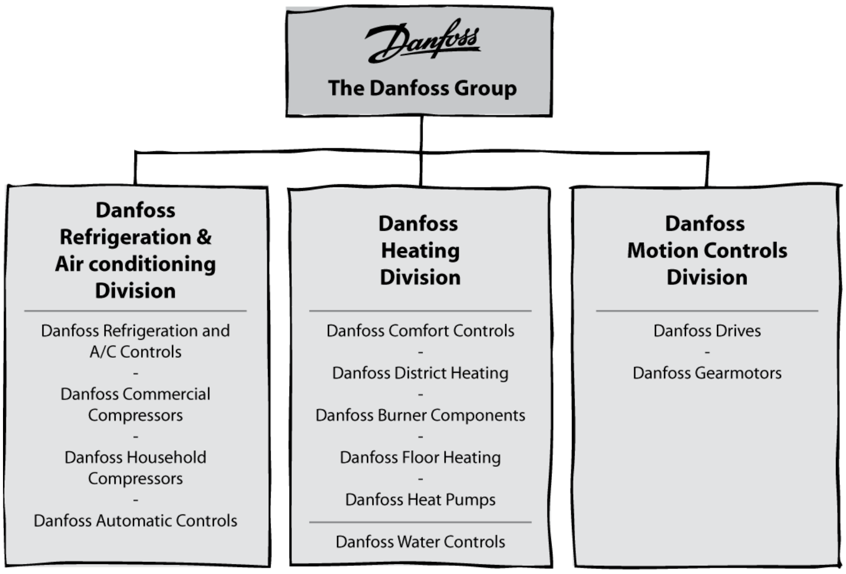

Figure 7.1. *The Danfoss Group is organised in three autonomous business divisions, which are sub-divided into multiple – also relatively autonomous – business units.*

Each business unit provides multiple product families and types, and often serves very distinct markets. All divisions have production facilities in Denmark and around the world – especially in Europe. Product development activities are on the other hand primarily kept in Denmark, although some product engineering occurs in other countries, when the producing factory has inherited the full responsibility of the products.

Danfoss Automatic Controls

The case study that has been undertaken in this research work is done in the business unit, *Danfoss Automatic Controls* (Danfoss AC), which is part of the *Danfoss Refrigeration & Air Conditioning Division* (fig. 7.1.).

Among other products Danfoss AC market solenoid valves for various applications. The solenoid valve products have been the subject for this case study.

The solenoid valve business

The solenoid valve business is relatively old. In the book *'Systematic design of industrial products'* the Danfoss solenoid valve product family was in 1976 used as a textbook example of how distinct product variants in a product family can be designed to have the greatest possible number of common form features [Tjalve, 1976] (fig. 7.2.).

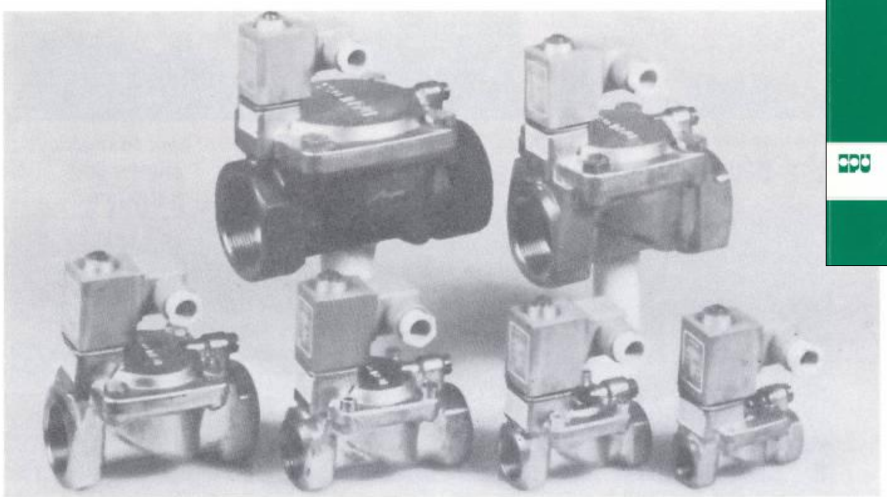

Figure 91 The separate products in a product series are usually so designed that they have the greatest possible number of common form features (Danfos Ltd.)

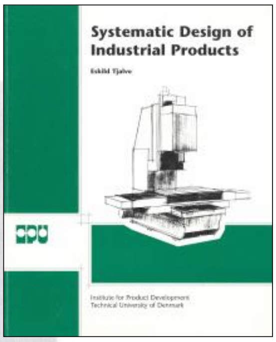

Figure 7.2. *In the book 'Systematic design of industrial products', which for years has formed a cornerstone in the education of engineers at the Technical University of Denmark (DTU) within the field of engineering design and product development, the Danfoss solenoid valve products served as a textbook example in how product variants are designed to have the greatest possible number of common features [Tjalve, 1976].*

30 years of product development and strategic acquisition of other manufactures of solenoid valves to accommodate new applications and markets or improve the existing business, has lead to an uncontrollable growth of product complexity as described in section 1.2. The current diversity within the solenoid valve products is illustrated in figure 7.3.

The test sample to which the research has been applied included 231 product variants, which account for approximately 2 million pieces sold and a turnover of nearly DKK 400 (€53-54) million pr. year.

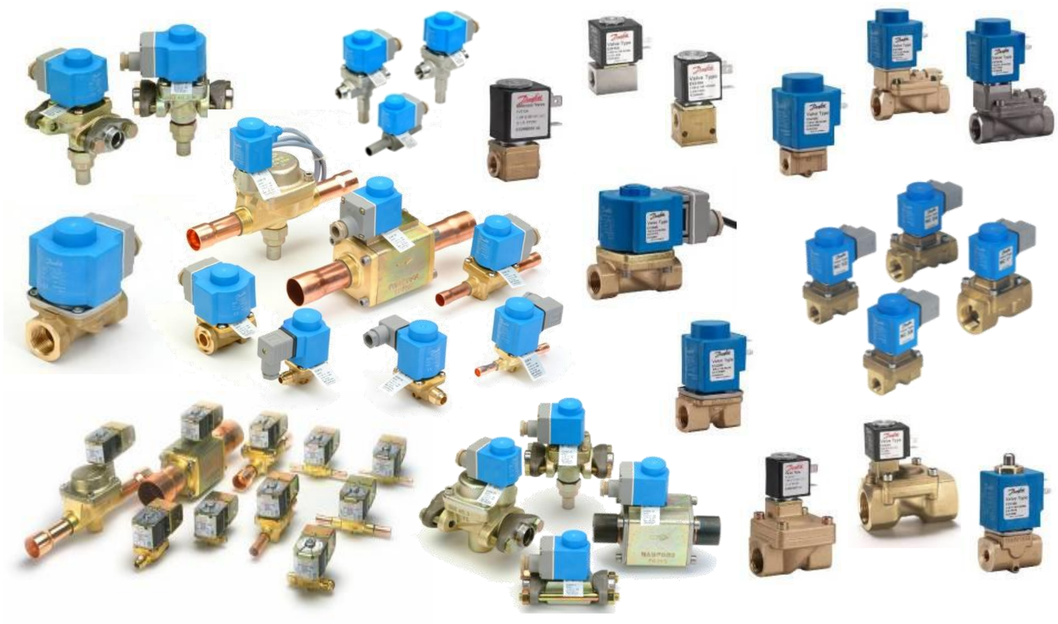

Figure 7.3. *Snapshot of the current diversity within the solenoid valve products at Danfoss AC. Each picture represent many more variants.*

Danfoss AC value streams

The solenoid valves are marketed through sales channels belonging to various business units, i.e. Danfoss AC can be regarded as a sub-supplier for other Danfoss business units. Especially, the business unit *Danfoss Refrigeration and A/C Controls* (Danfoss RA) take many products from Danfoss AC. Actually, approximately 2/3 of the Danfoss AC solenoid valves are sold for refrigeration purposes through the Danfoss RA sales channels, as the refrigeration market is where Danfoss has its origin and the refrigeration business is a traditional Danfoss stronghold.

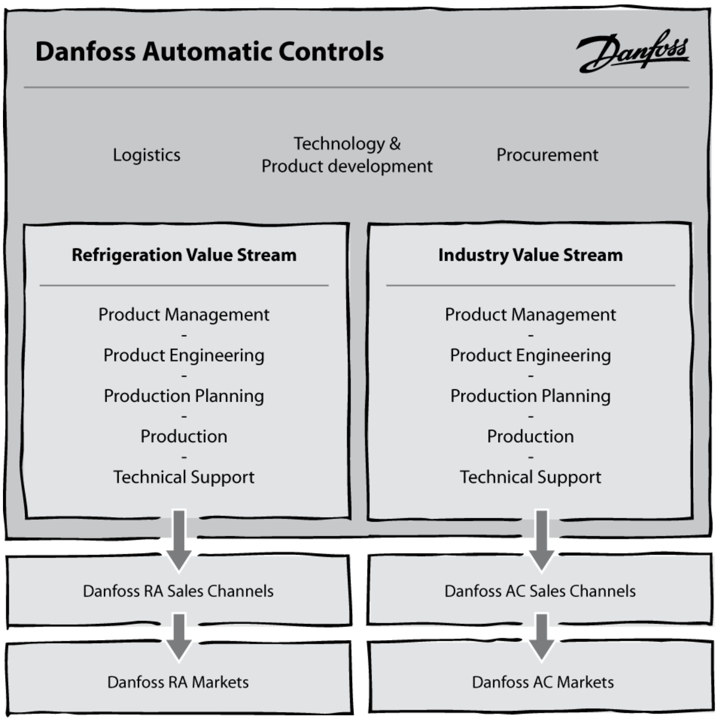

Figure 7.4. *The solenoid valve factory has in reality been divided in two separate factories (value streams) in order to serve the Danfoss RA markets and Danfoss AC markets, respectively.*

As a consequence of Danfoss RA's importance, the solenoid valve factory has a de facto split in to two factories within the factory. They are referred to as "value streams". One value stream serves Danfoss RA and refrigeration applications and one value stream serves Danfoss AC and other business units i.e. applications that are not related to refrigeration. Instead, the latter value stream produces solenoid valves for a multitude of industrial applications and in that sense it serves a much more inhomogeneous market than the value stream that serves Danfoss RA.

As illustrated in figure 7.4. the two value streams have independent product engineering, production planning, production, sales channels, etc., whereas they share other functionalities such as purchasing, logistics, and technology and product development.

The fact that the solenoid valve factory in fact has worked as two separate factories has often obstructed communication and consequently, coordination between the two value streams. As a consequence, the products share very few common features between the two value streams, despite the fact that the overall functionality and working principle of the products are the same.

Product development in Danfoss AC

In reality product development occurs in three different places in Danfoss AC's solenoid valve factory, by;

- Product developers in the Technology and Product Development department
- Design engineers in the value stream that serves the Danfoss RA markets
- Design engineers in the value stream that serves the Danfoss AC and other markets

The Technology and Product development department focus on long-term and strategic product development. They distinguish between three different types of development projects:

- *Market initiated projects*
  Projects that are initiated in order to gain new markets or to accommodate new trends or requirements in the existing markets
- *Customer initiated projects*
  Projects that are initiated to accommodate a request from a strategically important customer. A request that cannot not directly be accommodated by tampering the existing products
- *Technology projects*
  Long-term technology development projects

Design engineers in the two value streams handle customer requests that can be accommodated by making incremental changes to the product design. Also, they handle customer complaints on the existing products.

Besides the *standard option* they use the notions minor *special* and *major special*, which refers to how much the customer's request deviates from the standard option. In principle, major specials are projects that are outside the scope of the value streams and should be passed on to the technology and product development department.

In short the design engineers in the value streams handle everyday issues, whereas the technology and product development department handle more long-term and strategic projects.

A significant driver for product complexity has been the somewhat indistinct border between minor and major specials and a deficient coordination between the three sources of product designs.

Danfoss AC strategy

Danfoss AC has been working with a lean change process for several years. At the time of the beginning of this research, the production was well under way in a transformation process. But the products where not changed accordingly. The strategy was (and still is) to be a customer and market driven organisation i.e. to have a flexible product range and to accommodate the needs of the customers. The design of the solenoid valve products of the time did not support that strategy particularly well and some of the products also had a design that did not support the lean change process due to their complexity. It was at the time clear to management that the strategy and market trends had a mismatch with the product design. The inflexibility of the product design resulted in new components and variants being made frequently adding to the complexity of the total range, while only satisfying a narrow customer need. Thus, the combination of a market focus and a non-flexible product design lead to an uncontrollable growth of product complexity (section 1.2.).

As a consequence the management initiated a study of the solenoid valve product family in preparation for a re-design of the products in order to accommodate the new market oriented strategy. This research provided the approach to that study.

7.2. Product family assessment at Danfoss AC

As seen in the descriptive study I and discussed in section '4.3.11. Mindset' an important aspect of assessing a product family – apart from applying the actual tool described in part 6 – is to establish a mindset in the head of the users of the tool and other relevant stakeholders. Consequently, the case study work at Danfoss AC has included:

- *Educational initiatives*
  Different initiatives in order to establish a suitable mindset, i.e. introduce the relevant conceptual framework to the various stakeholders. These initiatives are described in the following section '7.2.1. Establishing a mindset'
- *Implementation of the PFMP^2 tool*
  Actual implementation of the actual prescribed support as it is described in part 6. This work is described in the section '7.2.2. PFMP^2 for the solenoid valve product family'

Finally, the resulting new product concept for the re-designed solenoid valve product family will be described.

7.2.1. Establishing a mindset

The work of establishing a mindset at Danfoss AC has included three different initiatives:

- "Platform thinking" seminars
- Information webpage
- Design game

"Platform thinking" seminars

3 one day seminars were arranged as a part of the Danfoss AC organisation's educational program. A total of 93 Danfoss AC employees participated in the seminars, including product developers, design engineers, production planners, production technicians, product managers, sales and marketing staff, and purchasing staff.

In continuation of some (at the time) existing *"Lean thinking"* seminars these seminars where named *"Platform thinking"* seminars on request from the Danfoss AC management, although the seminars did not focus solely on platform product development.

The seminars were structured as a set of lectures that should introduce different aspects of multi-product development:

- *Introduction to multi-product development theory*
  Introduction to the conceptual framework used in relation to multi-product development including product development based on platforms and architectures, modularisation, mass customization, etc.

- *Introduction to the PFMP tool*
  Introduction to the structural principles used in the PFMP tool, including object oriented modelling, customer, engineering and part view, part-of and kind-of structures, class definition, attributes, constraints, causal links, etc.
- *Lessons learned*
  Case stories and experience from other companies that have worked within the field of multi-product development. This part included lectures from external speakers, i.e. a consultant with experience from various companies and industries and a project manager from another Danfoss division where they have implemented product platform based product development.

Information webpage

As support to the seminars and in order to communicate the message to employees/stakeholders that were not able to participate in the seminars, an information webpage was created. The webpage basically contained a web-friendly version of the "platform thinking" seminars, i.e. an introduction to the conceptual framework behind multi-product development.

Design game

Although the "platform thinking" seminars lead to some discussions and the information webpage included a Q&A feature it was primarily one-way communication. In order to make the Danfoss AC employees take a more active role in the process it was decided to follow-up upon the "platform thinking" seminars by creating a design game that simulated the situation of managing decision-making at product family level and arrange one-day workshops to the Danfoss AC employees.

Two design game workshops were held at Danfoss AC with a total of 61 participants.

The objectives of the design game workshops were to make the participants gain insights into;

- *Product complexity*
  The participants should experience how product complexity occurs and the resulting implications that are caused by this product complexity
- *Dilemmas in decision-making*
  The participants should experience the complex trade-off that occur when trying to make decisions at product family level
- *Commonality effects*
  The participants should experience the effects of achieving commonality effects in the production/supply chain

The game setup

The participants were split in groups of 4-6 (i.e. 6 groups at each workshop). Each team represented an automotive company and were to compete with each other.

The basic concept of the game was that the groups should develop (build) cars from LEGO bricks based on simulated customer requirements (fig. 7.5.) and time the launch of their cars (products) according to simulated customer demand.

The profit made by each automotive company was calculated based on a more or less complicated mathematical model, which I will not try to explain in details. I will just note some of the factors that influenced a company's earnings:

- *Ability to meet customer requirements*
  A company's ability to design cars (i.e. build LEGO models) that match the customer requirements as they are simulated in the so-called *marketing memo* have direct influence on the price the company could charge, i.e. the better design the higher price. Figure 7.5. illustrate how the required features (in the middle) are built into a "real" car design.
- *Ability to time launch of products*
  Timing to launch the right products at the right time has great impact on a company's earnings. There different strategies to pursue. For instance, a company try to address markets that are

untouched by competitive companies or a company can try to steal market shares from competitors by addressing the same markets. Anyhow, timing is important.

- *Responsiveness to market changes*
  The ability to react swiftly on changes in the market is important. Throughout the game it various what market are the most attractive one. When a market suddenly becomes attractive it is important to be able to address that market before your competitors.
- *Reuse of design and components*
  To simulate commonality effects a company is rewarded if they reuse components (LEGO bricks) and/or design across various car models, i.e. the simulated production and development costs, respectively, are lowered in the mathematical calculation model.
- *Ability to manage supplies*
  A company's ability to manage supplies, i.e. ordering the correct bricks, the correct amount of bricks (not too much or too little), avoiding errors, etc., also have impact on the profit.

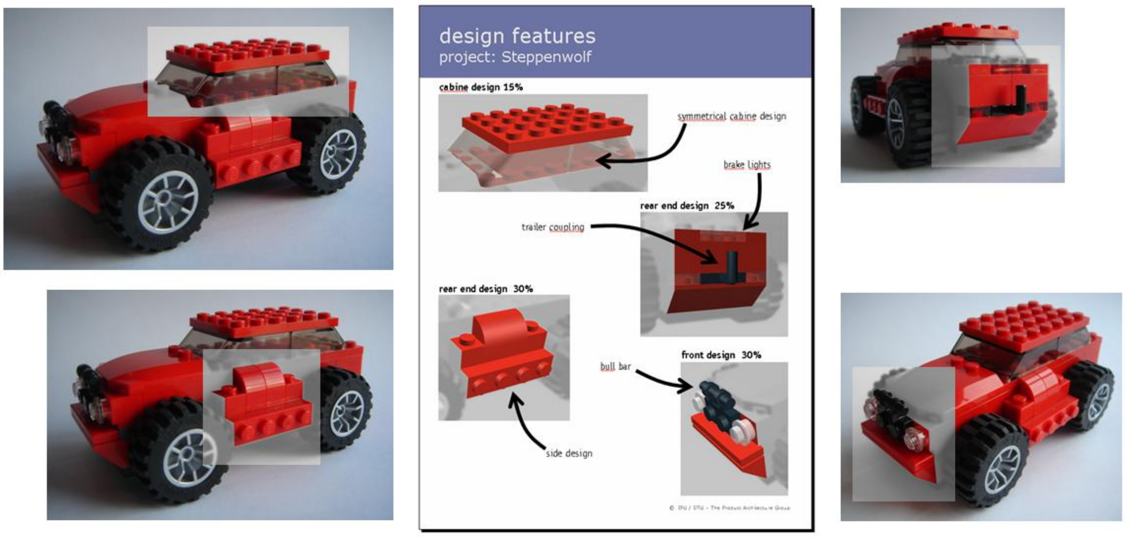

Figure 7.5. *An example on how the simulated customer requirements (the so-called marketing memo in the middle) are met by a car design.*

Experiences from the design game work shops

The design game workshops proved successful in many ways. First of all the workshops seamed to achieve the objectives related to product complexity, dilemma in decision-making and commonality effects as described above. More interesting is it that the participant got engaged in the game (fig. 7.6.) to such an extent that the sub-sequent discussion became a surprising source of input to the descriptive study I.

This was mainly due to the fact that the design game workshops had participants from various function (purchasing, marketing, production planning, etc.) and that these people with different backgrounds in the game were put in the situation of the product developer. As they naturally analysed the situation from a viewpoint related to their daily work, i.e. from a purchasing, production planning, marketing, etc., this setup provided many ideas of how to include aspects that should be considered in relation to other life phase systems.

Figure 7.6. *The competitive situation in the game got the participants surprisingly engaged in the situation.*

7.2.2. PFMP² for the solenoid valve product family

The modelling formalism as it is described in part 6 was applied to the solenoid valve products during a number of iterations. Initially the original PFMP formalism [Harlou, 2006] was applied in a so-called pre-project (section '2.5.2. Descriptive study I') to determine the potential of re-designing the products. As described in section '2.5.3. Prescriptive study' the pre-project lead to the start-up of an actual development project intended to address the product complexity.

During this development project at Danfoss AC the PFMP modelling formalism was refined and gradually extended to form the resulting PFMP² modelling formalism.

As the application of the PFMP² modelling formalism lead to some large poster (fig. 7.7.), this is not easily represented in the format of this thesis. As a consequence – and due to confidentiality issues - I am limited to present excerpts from the PFMP² for the solenoid valve product family as to illustrate how the modelling formalism has supported decision-making in the development project.

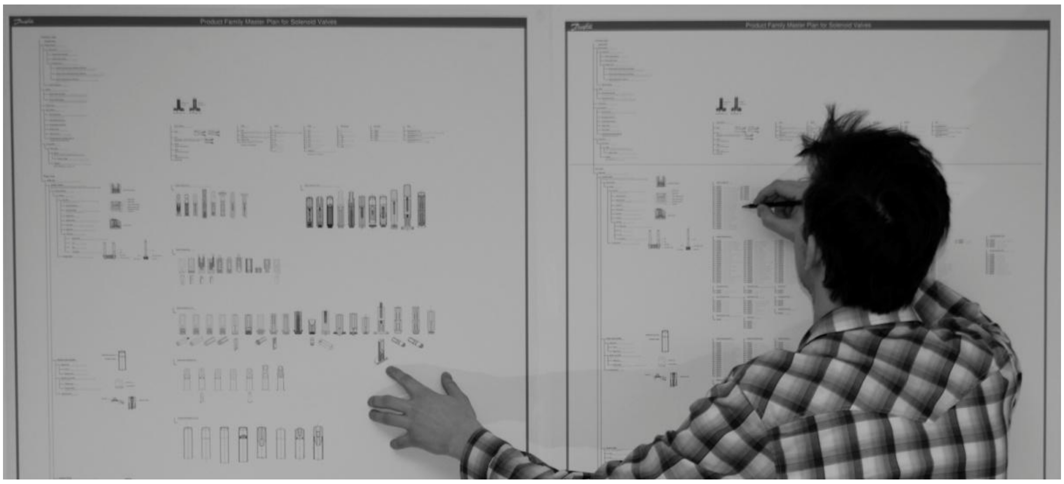

Figure 7.7. *Modelling the solenoid valve product family at Danfoss Automatic Controls lead to some large posters which are not easily represented in the format of this thesis.*

As described in part 6 the modelling formalism includes 4 different elements, i.e. the original PFMP modelling formalism and 3 additional modelling elements. The following extracts of the PFMP² from the Danfoss AC case study focus on illustrating how each of the added 3 elements link to the remainder of the modelling formalism. Consequently, the excerpts are presented in the subsequent sections:

- Extracts from the 'supply chain analysis'

- Extracts from the 'overview of the total product offering'
- Extracts from the 'critical design issues'

Extracts from the 'supply chain analysis'

The example from the 'supply chain analysis' takes its starting point in the way the valve actuator is joined to the valve body. Figure 7.8. illustrates the variety of assembly processing steps used to assemble the elements within the class *"armature tube/flange ass'y"*. The three right-most processing steps refer to three different ways to make these assemblies. This variety is caused by the use of different joining technologies – TIC welding, laser welding and soldering, respectively.

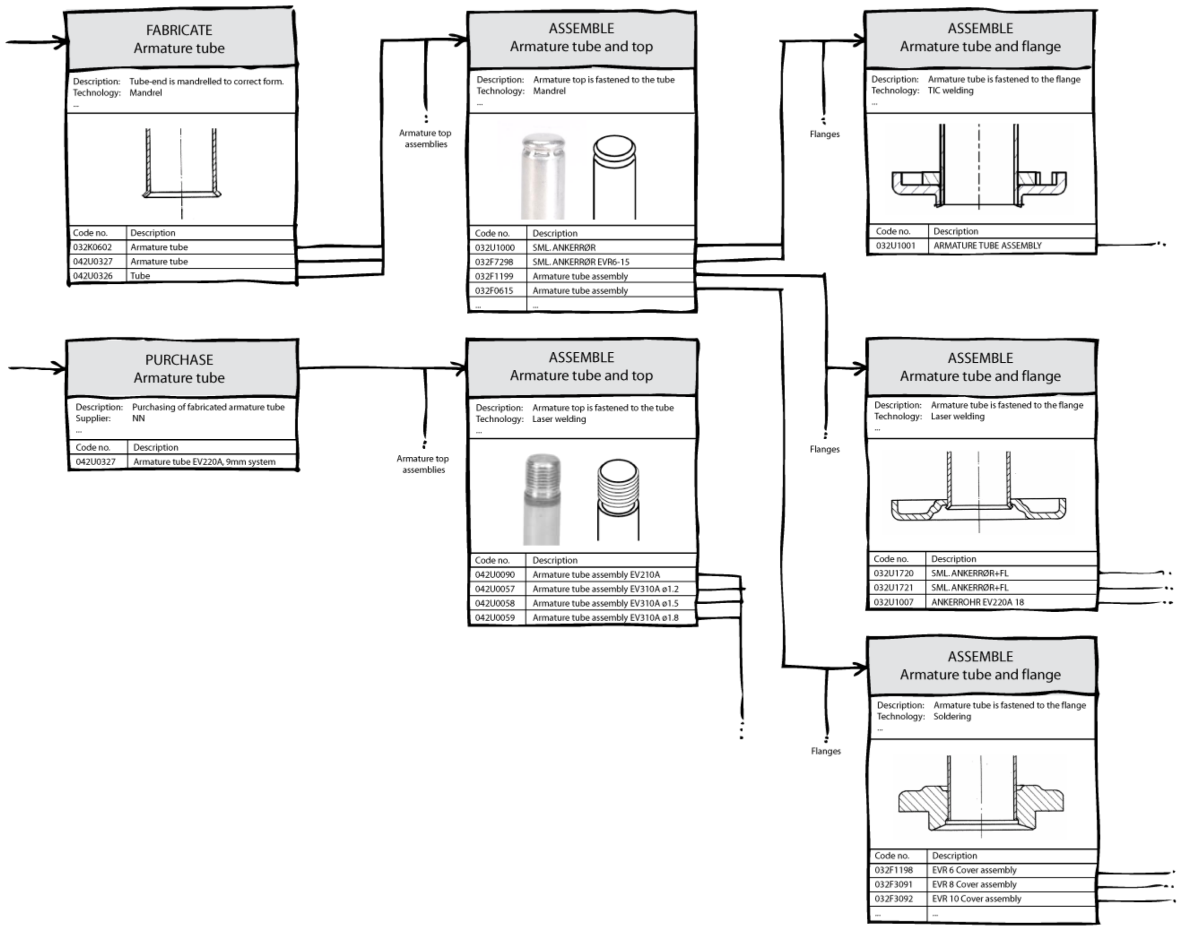

Figure 7.8. *Extracts of the supply chain analysis in the PFMP[2], which shows the variety of joining technologies used, i.e. laser welding, TIC welding, soldering and screws.*

From a product function point of view this variance in processes is non value adding, and potential types of process waste. It is natural to search for the reasoning behind the use of three different technologies and to ask whether this variety adds to the business. Cross references (fig. 6.29.) links the processing steps to the PFMP. The relevant extract of the PFMP is illustrated in figure 7.9.

Causal links to the customer view (fig. 7.9.) reveal that the choice of "armature tube/flange ass'y" only has an indirect influence on the allowed maximum working pressure for the solenoid valve, i.e. the size and thickness of the "armature tube flange" determine how big a pressure the solenoid valve can withhold. It can therefore be concluded that the joining technology is not something to which the customer has any direct requirements.

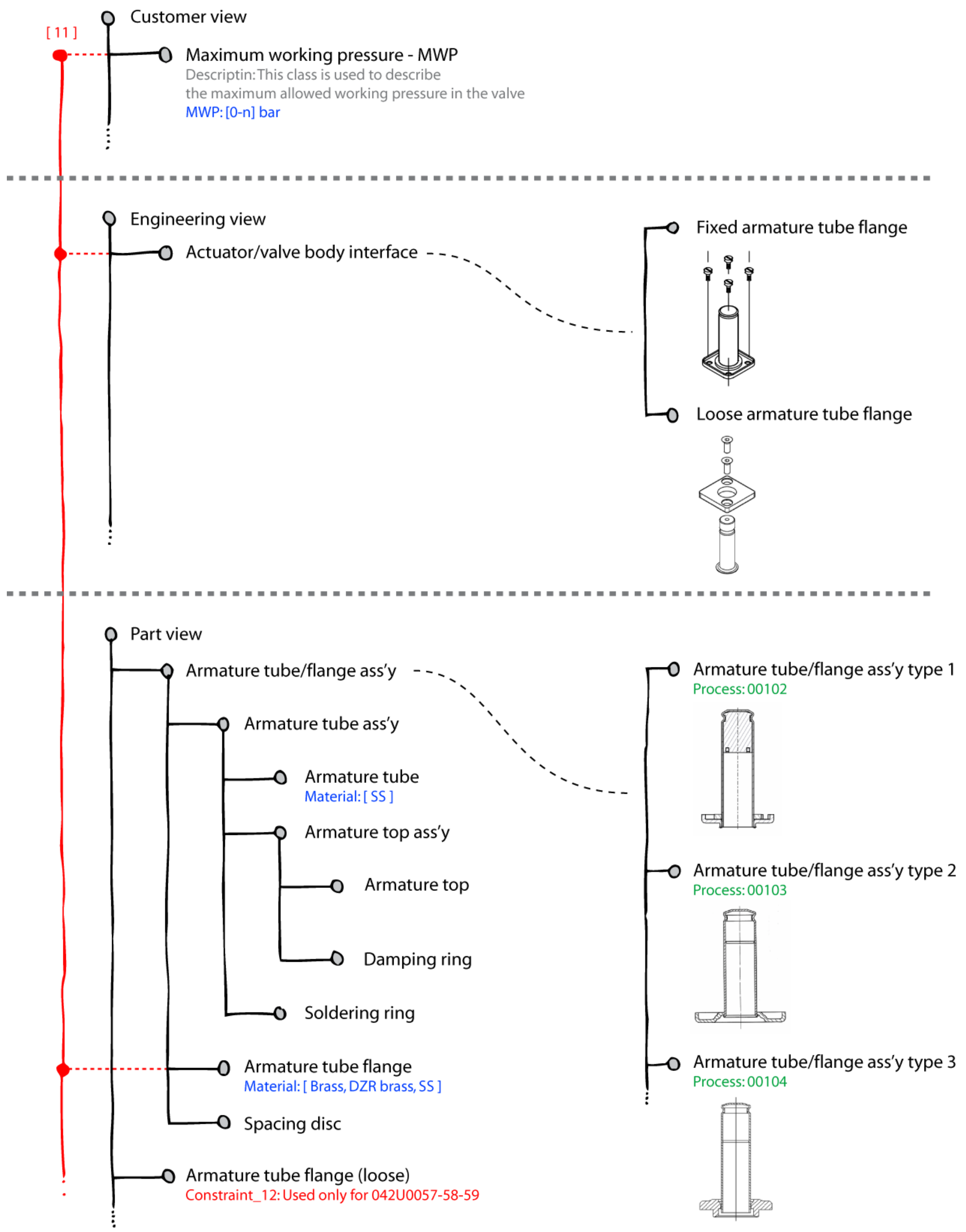

Figure 7.9. *Extracts of the PMFP² for the solenoid valve product family that illustrates the variety of armature tube/flange assemblies, which is connected to the variety of process technologies.*

It turns out that the variety of technologies used for joining armature tubes and flanges are caused by two things:

- *Historical reasons*
  Danfoss AC has strategically bought up several competing solenoid valve manufacturers and inherited the coherent products, product designs and process technologies.
- *Design decisions based on single product focus*
  When the market at some point requested low pressure valves (low MWP) the design engineers at Danfoss AC saw the opportunity to cut costs of the existing products. By replacing the current relatively thick brass flange that was soldered to the armature tube with a thinner and cheaper stainless steel flange they were able to significantly reduce the variable costs – from a single/few product(s) point of view. Joining stainless steel to stainless steel opened for the opportunity to use other and cheaper process technologies than soldering.

Although the variety of process technologies seems to be the best solution seen from a variable costs perspective, the multitude of joining technologies is a significant driver for fixed costs, e.g. in terms of costs related to maintenance of the equipment and the necessity to have in-house competencies within each technology.

Furthermore, each of the joining technologies sets requirements to the detailed design of the product, meaning that armature tubes and flanges designed for TIC welding cannot be joined together using laser welding and vice verse. Not only does the lack of flexibility in the product design require many combinatory constraints in the PFMP, it also drives product complexity in the sense that the variety in processes imposes variety in the product design similar to the way variety in customer requirements call for product variety. Consequently, more parts and assemblies need handling in the upstream supply chain.

Basically, the current design and production setup is based on economies of scale. The future design and production setup should be based on economies of scope which requires the use of processes that are more flexible and can accommodate a greater variety of products.

Extracts from the 'overview of the total product offering'

Figure 7.10. shows a section of the PFMP in which the variety of working principles (organs) that are used to create the actuating functionality in the solenoid valves can be seen. A total of four actuator organs exist in the product family – one NC actuator organ and three NO actuator organs (type 1, 2 and 3).

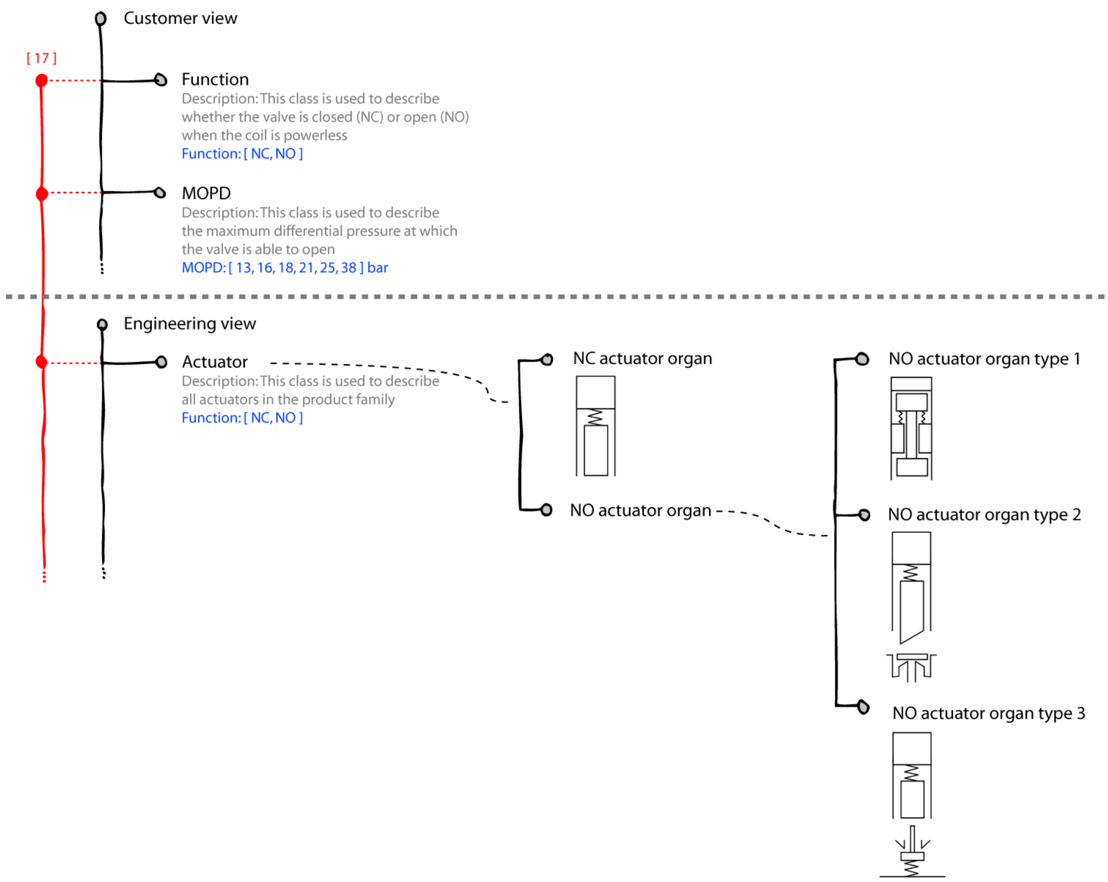

Figure 7.10. *Extracts of the PMFP[2] for the solenoid valve product family that illustrates the variety of actuator organs in the present product family.*

NC and NO are abbreviations for *normally closed* and *normally open*, meaning that the solenoid valve is either closed or open when the coil is powerless. As illustrated in figure 7.10. the choice of "actuator organ" has causal links to the "function" and the "MOPD" (maximum opening pressure differential) classes in the customer view. The latter can be perceived as an expression of how "strong" the valve is, which is influenced by many factors (concepts, dimensions, materials, tolerances, etc.).

The conceptual design of the various actuator organs set limitations for how much force it is possible to derive from the design, but still the actual performance of the actuator relies heavily on details in the physical realisation of the organ.

The variety of NO actuators has never been tested systematically, but it is a common perception that the type 1 and 2 actuators can only be used for relatively low pressure applications, whereas type 3 can be used for higher pressure applications. Still, the difference is somewhat speculative.

If we consider the distribution of turnover, sales volume and number of variants across the four actuator organs (fig. 7.11.), it is clear that NC actuators contributes significantly to the business in comparison to the NO actuators (Turnover: NC=95%, NO=5% and Sales volume: NC=97%, NO=3%).

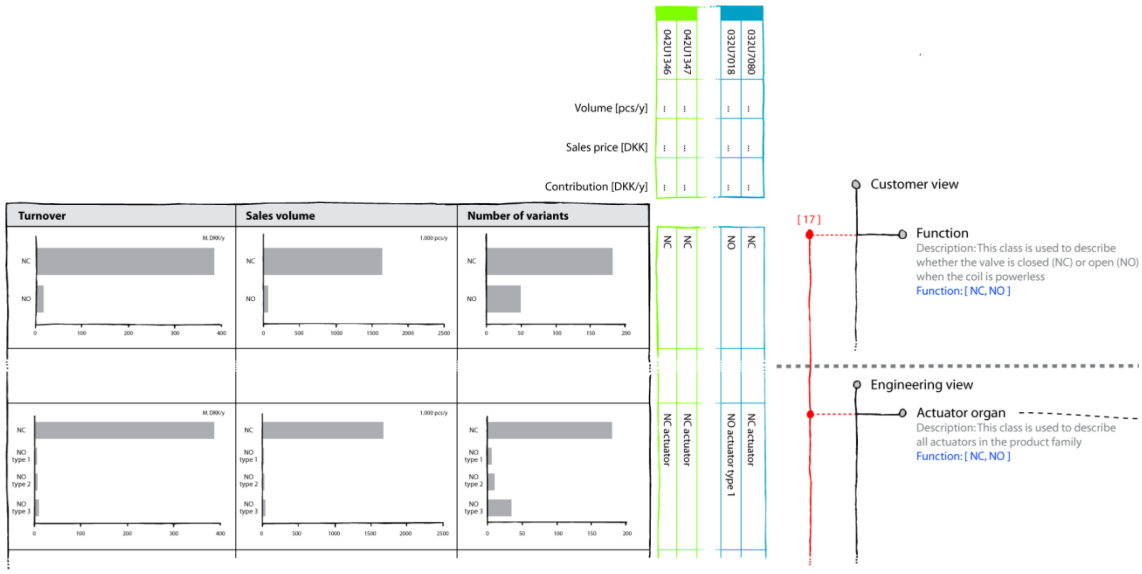

Figure 7.11. *Extracts of the overview of the total product offering in the PMFP², which illustrates how turnover, sales volume and the number product variants are distributed across the different actuator organs.*

Due to the relatively little significance to the business, it seems undesirable to use three different organs to serve the same purpose of providing a "normally open"-function. This is even further supported by the assumption that the NO valves has a significant contribution to the product complexity as 50 of the total 231 valves are NO valves (i.e. 22%) (fig. 7.11.). Compared to how much the NO valves contribute to the business, this amount of product variety cannot be justified.

Consequently, a common NO actuator organ should be pursued if a re-design process is started.

Extracts from the 'critical design issues'

An example of the application of the modelling formalism for critical design issues is illustrated in figure 7.12.

The travelling distance (lifting height) of the armature when opening/closing has great importance to the performance of the valve. Basically, the lifting height determine a trade-off between force and capacity – force in terms of MOPD (i.e. the maximum differential pressure at which the valve can open) and flow rate (i.e. at what rate (m^3/h) does the media flow through the valve). The higher lifting height the greater the flow rate. But because the solenoid actuator lose its strength as the air gap (when the coil is powerless) between the armature and armature top (=lifting height) increase, capacity will be gained on the expense of force (i.e. MOPD). 1/10 of a millimetre can have critical consequences on the MOPD performance of the actuator.

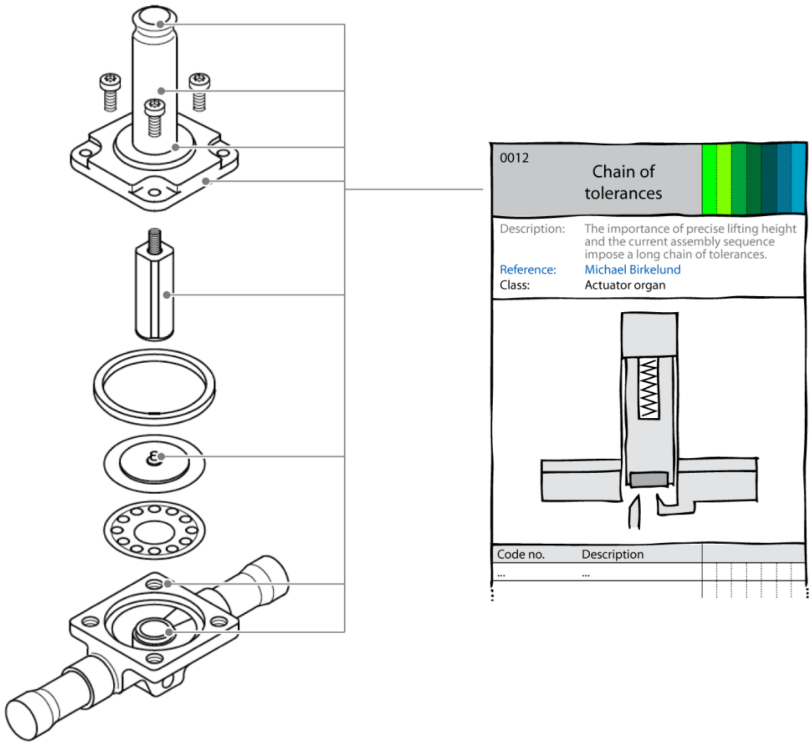

Figure 7.12. *Extracts from overview of critical design issues in the PFMP², which illustrates the chain of tolerances that is caused by the importance of a precise lifting height and the current assembly sequence.*

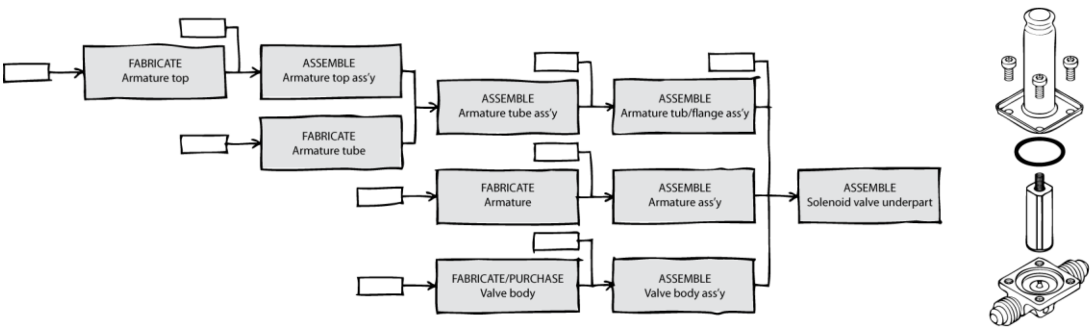

Figure 7.13. *Conceptual overview of the typical assembly sequence in the present product family.*

The current design and assembly sequence illustrated in figure 7.13. results in a long chain of tolerances that are all accumulated in the final assembly of the solenoid valve. That is, the lifting height is determined by the dimension – and therefore also the preciseness – of a long list of components and processing steps:

- Armature assembly length (incl. all components in the assembly)
- Armature tube length
- Armature top length
- Height of diaphragm assembly (not included in figure)
- Relative position of orifice in valve body
- Precision of the armature tube and top assembly process
- Precision of the armature tube and valve cover assembly process
- Precision of the valve cover and body assembly process

Consequently, relatively high demands to manufacturing and processing tolerances are set to all of the above mentioned elements. This is, not surprisingly, a costly affair. Even more so, because the tolerance chain design issue is more or less relevant to all product variants.

A possible subsequent re-design process should address this issue and minimise the need for costly tolerance demands.

7.2.3. The new product concept

The work with the PFMP² modelling formalism constituted a basis from which at first ideas for a new product design concept was generated. Management showed confidence in the project and it was decided to proceed with detailing and implementation of a new product design and a coherent production setup based on the initial design concept.

At the time of writing the project has been running for more than four years with a significant budget. The initial decisions and actions were taken based on the use of the modelling presented in this thesis. The following section briefly elaborates on the new product concept and the expected impact of the project in order to demonstrate the potential outcome of assessing a product family. Due to a confidentiality agreement with Danfoss AC vulnerable design details and economical figures have been subject for censorship.

First, I will present the overall product concept which is based on modular building blocks. Second, I will (to the extend it is possible within the confidentiality agreement) describe how the issues, which was exemplified in the extracts of the PFMP² modelling formalism, i.e. section -. Finally, I will present the expected impact of implementing the new product design concept.

Modular building blocks

The new product concept is based on a modular building block system. During the design process it has been emphasised that constraints should be avoided, so that the building blocks can be combined freely. This is thought to be one way of making the new design future-proof and avoid budding of new complexity-adding design in the nearest future. The modular building blocks allow configuration and combination of nearly three times the number of product variants that are offered in the existing product family.

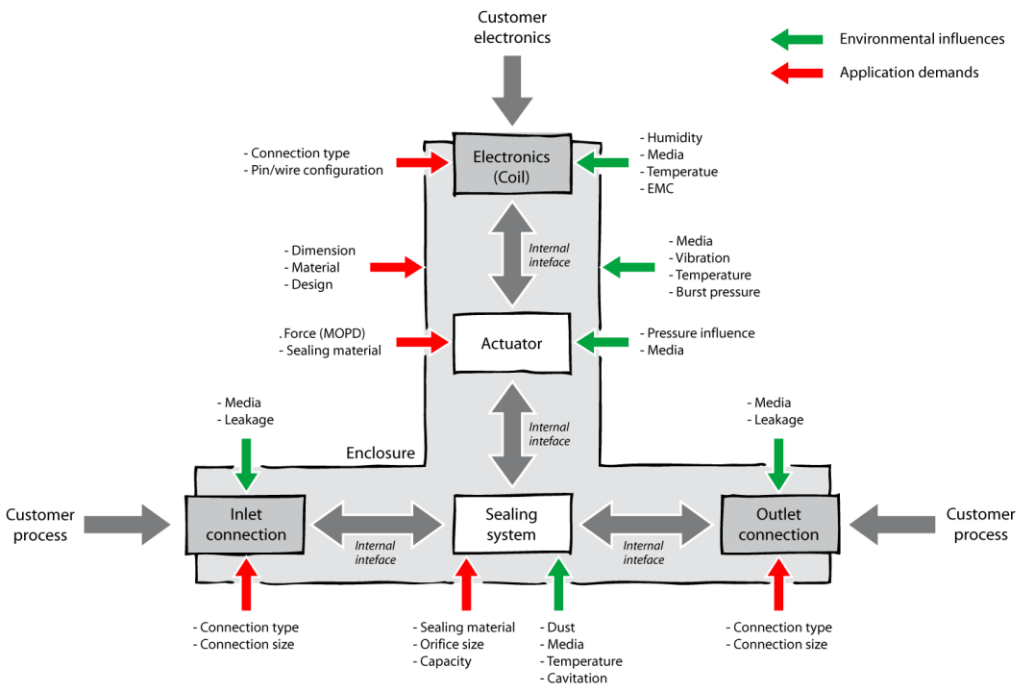

Figure 7.14. *The solenoid valve specification model. The model indicate how and where specifications (application demands and environmental influences) are built into the product.*

Identification and documentation of interfaces played a great role in the design process. To support this task Danfoss AC established a specification model (fig. 7.14.) to identify interfaces and define how and "where" product specifications (application demands and environmental influences) should be built in to the solenoid valve. Though, the model is very simple, it contains many aspect of those presented in relation to the concept of a product architecture, and the model was occasionally referred to as the "architecture".

Figure 7.15. illustrates the building blocks in the new product concept.

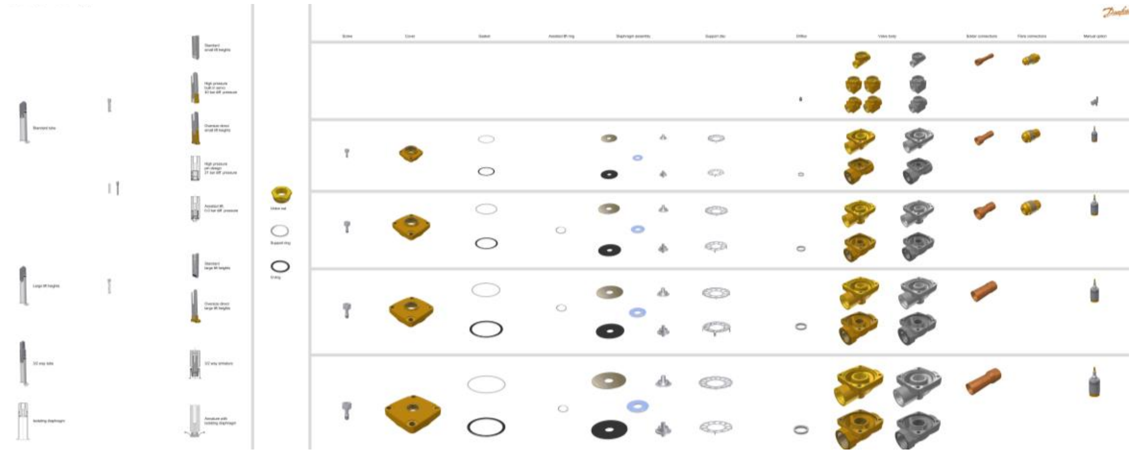

Figure 7.15. *The modular building block system from which the future product are to be derived. Actuator building blocks (left), union nut (middle) and valve body building blocks (right).*

To the left in figure 7.15. is shown the armature tube and armature assemblies that are used to generate the needed actuator functionalities. The right part of figure 7.15. shows the building blocks that are needed to generate the needed valve body variety. The valve body building blocks are made in five sizes – one system for the smallest direct-operated valves (the topmost) and one system for all servo-operated valves and large low pressure direct-operated valves (the four bottommost). In between the actuator and valve body building blocks the interfacing parts are shown, i.e. a union nut, a support ring and an o-ring, which are used to join all actuator and valve body configurations.

This lead us to explaining how the issues described in section - has been addressed in the new product concept:

- Non value-adding variety of assembly processing steps
- Non value-adding variety of actuator organs
- Inconvenient chain of tolerances

Non value-adding variety of assembly processing steps

As mentioned above all actuator configurations are joined to the valve body using a union nut (fig. 7.16.).

Seen from a variable cost perspective this is a very costly way of joining the two parts compared to the various welding and soldering technologies and this was the reason why the union nut solution has been opt out when designing solenoid valves in the past. But because it has been valued highly to find process solutions that were flexible and could accommodate a higher degree of product variety in accordance to economies of scope, the union nut solution became an attractive alternative.

Furthermore, the performance of the union nut is superior to the alternative welding processes as regards ensuring reliable quality in the assembly process.

Basically, Danfoss AC reckon that the upside of not having to maintain various welding competencies in-house including equipment maintenance, quality control, concomitant product complexity, etc. eclipse the downside of the relatively high variable costs connected to the union nut solution.

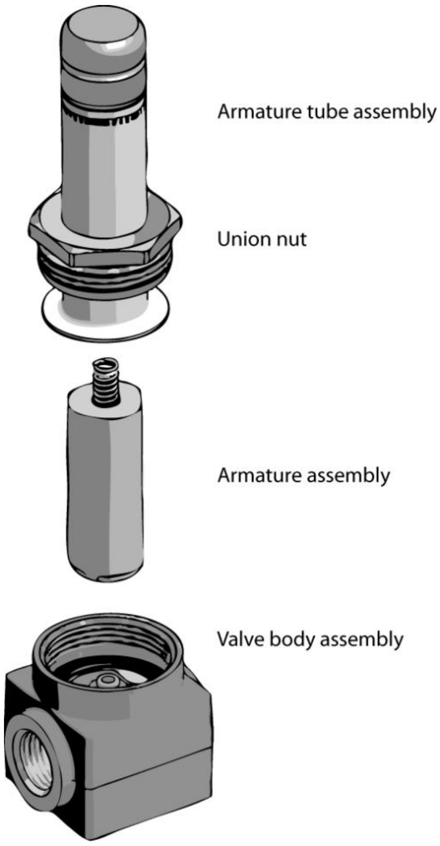

Figure 7.16. *All actuator configurations are in the product concept mounted to the valve using a standardised union nut.*

Non value-adding variety of actuator organs

The solution for the issue described in section 'Extracts from the 'overview of the total product offering'' may seem obvious; one working principle (organ) should serve all application. Applying this idea in the real world showed somewhat complicated, though, and it took a lot of engineering ingenuity to come up with a so-called *normally open* (NO) design, which could accommodate the needed variety of NO applications.

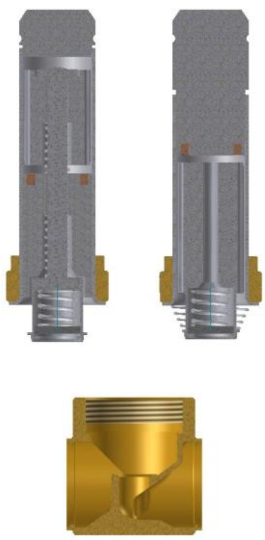

Figure 7.17. *Entirely encapsulation of the normally open (NO) functionality in the actuator means that NO (left) and NO (right) actuators are freely interchangeable.*

In the end the project team managed to squeeze enough pulling force from a design that resembles the existing "NO actuator organ type 1" (fig. 7.10.). The reason to strive for this solution despite it was probably not the best technical solution in terms of pulling force, is the possibility of encapsulation the entire NO functionality in a building block, which is completely independent on the valve body. In this way NC and NO actuators are freely interchangeable (fig. 7.17.).

Inconvenient chain of tolerances

The design issue concerning a long chain of tolerances, which was described in section 'Extracts from the 'critical design issues'', has been addressed by rearranging the assembly sequence and introduce a test of the critical lifting height just before the final assembly step. A typical example of the rearranged assembly sequence is illustrated in figure 7.18.

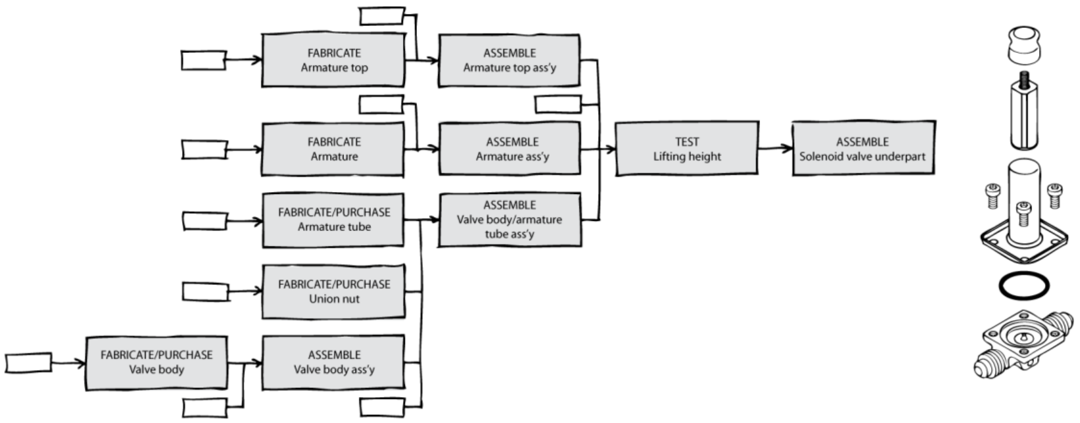

Figure 7.18. *Conceptual overview of the typical assembly sequence in the future production setup.*

In the new design all armature tubes are open-ended, meaning that it is possible to make the laser welding of the armature top assembly to the armature tube the final assembly step. In this processing step - just before the welding - the lifting height can be calibrated by the means of a simple manoeuvre, which I cannot reveal due to confidentiality.

As a consequence, tolerance requirements for all processing steps - assembly and fabrication of parts – can be slackened.

Benefits from the new product concept

As products based on the new concept are still to be launched at the time of writing the exact impact of the re-design of the product family is still questionable, although financial estimates have been recalculated continuously throughout the project. Furthermore, the lack of adequate economical models for total cost calculations also damages the credibility of the estimates. Having this mentioned, the latest estimate predict a total cost reduction of 26%, i.e. of all costs related to running solenoid valve business including manufacturing, purchasing, development, marketing, etc.

Still, the figures seem promising, and two outcomes of the project that cannot be doubted are the compactness of the new valves and the reduction of product complexity.

Compactness of future solenoid valves

The magnitude of this re-design project has entailed the development of the next generation solenoid valves, meaning that the design team could wipe the slate clean and start from scratch. Summarising more than 30 years of experience and expertise within the solenoid valve business have enabled the design to shrink the design without any loss of performance (fig. 7.19.).

The smaller and lighter design has many beneficial consequences in relation to material consumption, packaging, inventory and transportation. But most importantly is it, that the smaller design is a strong selling point in the competition for market shares.

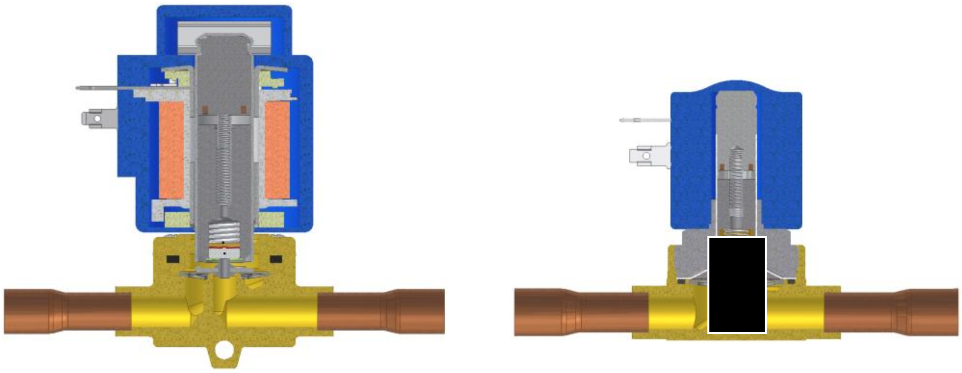

Figure 7.19. *The new product design (right) is notably smaller than the corresponding present product (left); exemplified here by the current single best selling product variant (~160.000 pcs./y.).*

Complexity reduction

Figure 7.20. lists the number of different parts/assemblies in the present and new product family, respectively.

Components	**Present product family**	**New product family**
Armature tube assemblies	41	8
Armature assemblies	62	17
Diaphragm assemblies	42	20
Valve bodies	152	73
Coil components	98	64
Total	**395**	**182**

Figure 7.20. *Number of different parts/assemblies in the present (left) and new product design (right).*

As discussed in the introduction complexity is not entirely equal to the pure number of physical parts and assemblies. Still if one keep in mind that the present product design posses relatively many constraints and requires a greater variety of production technologies whereas the elements can be combined freely in the new product concept and production processes handle a greater variety of products, it can be argued that the numbers in figure 7.20. at least are not lying. If anything, they are not telling the entire truth, as one could argue that the complexity reduction is greater than the well over 50% reduction in parts and assemblies indicates.

7.3. Conclusions from the product family assessment at Danfoss AC

At the time of writing this thesis, I have followed the case project at Danfoss for five years. At first, it was a minor pilot study (the Descriptive study I) and later on it has gradually expanded and as of today it is a relatively large development project (compared to other ongoing projects in the business unit) with 15+ full time resources and a significant annual budget. Most of my experience from the work has come from the regular contact with the engineering designers in the project team. At times I have been present at the company on a daily basis.

To watch how they have incorporated the working patterns and methodologies and adopted the PFMP[2] approach has been a valuable source of input to the validation of the research. It is also these everyday experiences that have convinced me about the usefulness of this tool, yet, the actual research validation is not based on this feeling alone but on a reviewing process that also included academic and industrial reviewers who were not part of the case project. Anyhow, I still regard the feedback from the project team in Danfoss as the most valuable input, as it provides details on how the research results have been adopted and applied in a real life industrial setting.

Despite the five years of implementation I would still regard this study as a rather preliminary one. There are many details that have not been addressed and there is much further work to be done. Besides the tool itself and the mindset activities (section 7.2.1.), there is still the challenge related to the whole change process, and the shift from a single product development organisation to a multiple product development organisation – i.e. to work with a modular platform setup for products and production. It is outside the scope of this research, but it still has to do with the research objectives, i.e. "to enable effective and efficient production of product variety".

Other factors have changed at the case company during the five years of this project. There have been numerous organisational changes, yet they have only had minor effects on the project. One thing though, has had quite a big impact on the project and even proven the worth of this research; some engineers left the team while new people joined during the five years as a consequence of natural changes in the organisation, people leaving their jobs etc. The PFMP[2] proved to be the place to go for a quick introduction for new people and for the leaving engineers to store parts of their knowledge.

I have documented these different inputs as notes about the situation and statements from people. After having discussed with my colleagues at DTU, I have decided to present an exemplar of statements from the design team and from the review panel and divide them into the four validity schemes presented by [Pedersen et al., 2000], i.e. the validation square.

Theoretical structural validity

"This tool holds highly relevant information – it ties together elements that I usually have to spend many hours to find in various IT systems – The approach of gathering the information on one piece of paper seems to be very feasible"

Project manager, Danfoss Electronic Controls & Sensors

"I support the basic idea of linking production flow – as a kind of value stream map – with the product structure. It is now possible to see the consequences of design decisions in the production and vice versa, I mean seeing the design constraints imposed by the processes and production setup. One might use this approach to design for manufacture, DFM, as well as manufacture for design, MFD"

Production manager, Danfoss AC

Empirical structural validity

"I think our product range is very representative for the whole controls industry"

Design engineer, Danfoss AC

"We are a very typical OEM and wholesaler supplier, building control components of medium complexity and selling them in a business to business environment"

Marketing manager, Danfoss AC

Empirical performance validity

"I have found so many components that should have been closed long ago – I did not know they were still around",

Design engineer, Danfoss AC

"The tool can tell us how to move on from here, and it certainly gave us an overview that we have never had before. It really threw 30 years of complexity right in the face on management – no one can ignore this anymore"

Project manager in product development, Danfoss AC

"This is the first time I have actually been able to see our complexity and the effects of it. Moreover, I now get an indication of how we can get rid of it – I like the object oriented modelling approach and the way it is linked to the production"

Production manager, Danfoss AC

"This is the best foundation for decision making I have seen in decades", vice president, Danfoss AC
"Our management team has not been able to address the issue of complexity before now. Now we have a very clear picture of the internal problems in our organisations and we are now able to act and to start improving our business"

CEO, Danfoss AC

Theoretical performance validity

"I would expect this tool to work in a service environment as well"

Management consultant, Implement

"This tool is clearly applicable to other component industries than Danfoss and to other product types than solenoid valves. I have been in three other companies before Danfoss and they would all benefit from this study"

Design engineer, Danfoss AC

"If we were to use this tool, I would need another resolution, I mean the scale of details would have to be different, because our products are much more complex than solenoid valves. But I am sure it would be possible and applicable"

Vice president, Aker Solutions, Norway

The general impression from the feedback from the 29 industrial practitioners, who gave the most detailed feedback, is that they clearly recognise the applicability of the tool. Some of them stress that it will take a long change process to implement and update the tool should they choose to use it on a long term basis. Others note that someone should have the responsibility to keep the $PFMP^2$ model updated.

Generally speaking I do think it is fair to conclude that the tool has proven its validity and that it does have "Usefulness with respect to a purpose" – the purpose being to support decision making on product assortments in order to increase the effectiveness and efficiency of organisations that are developing, marketing and selling mechanical products.

7.3.1. Does the tool meet the requirements?

The general picture from the interviews with reviewers and the feedback gained throughout the nearly five years in the project team is that the research results due to a large extent help the design team. A more specific evaluation of the research has to be compared to the initial requirements stated in the beginning of the thesis. The following discussion is a discussion of such a comparison, based on the feedback received during the project. The requirements were;

- Customer perceived product offering
- Value of variety
- Causal links
- Product structure
- Life phase system relations
- Point of variegation
- Production/supply chain system

- Strategic importance
- Critical design issues
- Format of the tool
- Mindset

The general impression is that the tool does provide an overview of the customer perceived offerings, value of variety, the causal links, the product structure and the life phase system relations. All reviewers note that the tool is a good way to map the relations between product structure and production setup. All persons involved in the study stress that the tool deals with the above requirements to a satisfactory level.

However, the point of variegation is not clear to everybody and the tool does not comply fully with that requirement. Some quotes regarding the point of variegation is stated below;

"I get the point of it when you explain the notion of variegation, but the representation in your model is indirect"

Project manager, Danfoss AC

"The point of variegation is not explicitly shown on the poster, but the consequences of variegation is clear, as I can follow the number of variants through the production"

Production manager, Danfoss AC

The feedback relating the production/supply system is of a more blurred kind, as some of the reviewers would like to have seen more details in the production model. Two of the reviewers were accustomed to the value stream mapping technique [Rother & Shook, 1998]. They would have liked to see more detailed information on push and pull cycles as well as the ability to map flow of information. Some of this critique might be a consequence of that fact that these two reviewers have used the value stream mapping technique to optimise production flows and to implement lean in a production. I would argue that the detailed listing of information flow is of more importance when you move from relatively Push based production system to a more pull based production system like a kanban system. This is – I think – one of the reasons why these two reviewers have shown particular interest in this feature.

Some reviewers find it hard to explicitly see the very complex idea of "strategic importance" in the tool. What is strategic importance and how does it show? One of the reviewers coined the issue like this;

"The strategic importance of one product variant might be in contrast to the importance of another product. It all depends on the strategy off course, and if you do not have a clear indication of the strategy, you will not be able to show the strategic importance of product X and Y, simply because you do not know it. I do not think that you can in fact show the strategic importance as a characteristic of one single product variant over another single product."

There were also more general comments on the use of the tool, and some were missing more information on the business and marketing research aspects:

"In order for me to really make a sound decision on this basis, I would like to have seen more statistics on customer behaviour and habits as well as preferences. As of now, the tool only show our own perception of the world"

"The strategic importance is one thing – our customer is something else. And I think you need to include the customers more than the strategic importance. Strategy is what we decide but customer expectations is what matters"

The critical design issues were a popular feature in the tool, and the general impression is that it the tool meets this requirement. In the case project, it even turned out to reveal and gather certain important design characteristics that were later changed in the future product design.

"I like the possibility to show critical design issues like you have on the poster. It serves as a checklist that sums some of our critical design characteristics – those that we might need to chance or at least handle with precautions."

The format of the tool was not a requirement as much as it was a desirable characteristic. The format is visual and graphical and it received very positive reactions from all stakeholders and reviewers. The general feedback is that it breaks with traditional media in a company, i.e. data and information that is stored on a computer system. A few example quotes pinpoint the reactions;

"This is the first time I really see our products and our production"

"The fact that you have been able to put down all our bill of materials in one piece of paper is a remarkable achievement – And it all shows on the poster"

"The constraints between product design and production must be very clear to everyone. Let us now hope that the consequences of product design in production is of a more optimum nature in the future"

Other limitations apart from the requirements

The list of initial requirements is one issue. Another issue is the features that came to the minds of the reviewers when elaborating their viewpoints on the requirements. The most important of these are the following three aspects:

The change process

Several reviewers in Danfoss state that there has to be a change process in order to keep the findings updated and implemented. The PFMP[2] is a picture of the state of the product family at a certain point in time. If it is not updated according to the growth of the product family, the overview will become obsolete at some point. In relation to that issue follows the issue of changing working patterns and habits. If the company does not change its product development procedures, then the complexity will keep on growing. The tool only highlights the problems, but does not directly solve them.

The question of reallocation of resources

During and after the process of making the poster and visualising the complexity in a product family there will be a need for resources. During the process it takes quite a few man hours to extract and refine data from various sources. Some of the reviewers asked for procedures and ways to go about the work in the most efficient way. I guess it is a matter of management attention rather than standardised working procedures, as all companies are different.

The graphical and visualisation skills of the employees

Several of the people involved in this study provided data but stated that they had no overview of the data, and had no ideas on how to make such an overview. One engineer gave a comment:

"I have all the information inside my head, by I do not know how to visualise it to others in a smart way. It seems like this tool is a good way to do it, but I would not be able to build in myself even after training. It seems as though it takes some sense of aesthetics to create an overview of our complex products – and I do not have that sense."

In other words, management has to choose people with the right mix of skills. An obvious pitfall is to choose the best product expert among the engineers. He/she might tend to focus too much on details and might not have the right skills to make a visual poster presenting a broader overview – with more focus on overview than detail.

The limitations of the tool and indications of further work to be done are elaborated in the reflection in Part 8.

7.3.2. A comment on the validation of the research

The industrial reviewers had diverse relations to the project. Some have had no role in the project whatsoever and come from different companies, while others have taken a very active part in the study and as they have been part of the project team forming the case. Most of the external (i.e. not from Danfoss AC) reviewers have received a presentation of the tool led by myself.

Consequently, some got to know the tool very well and thereby provided very useful comments, yet they were also the most problematic sources of validation seen from a research point of view, as they gradually developed a more biased view on the tool and the project. The external reviewers are somewhat more unbiased, but they have a less elaborated view on the tool as they did not have time to apply it on a real case, thereby developing a deeper understanding of their own and possibly more detailed viewpoints. Furthermore, their view on the research results would potentially be a subjective one, as the presentation of the tool was done by the researcher and not from an objective source.

That paradox is characteristic for this research and it is formed by the preconditions of the study and cannot – to my best knowledge - be changed within the limitations of a study like this.

7.3.3. Experiences from the implementation

The work of implementing the research result at the case company brought a number of positive effects and inexpediencies regarding the practical application of the PFMP^2 modelling formalism.

Collecting the data

It has been mentioned several times in this thesis that many manufacturing companies have great difficulty in retrieving the vast amount of information and data that is associated with the operations in a modern and possibly global company.

Carving out the relevant data and information is therefore a discipline that involves spending hundreds if not thousands of hours in various data systems, such as the typical CAD, ERP, PDM, and data warehouse systems, present in most modern companies. But in order to retrieve information on all different variants, their flow through production, their reason to be, their contribution to business and their place in the product family etc. I found it necessary to walk around in the organisation and get locally stored databases, hardcopy drawings and other types of information that was otherwise inaccessible.

Most ERP and PDM systems have the ability to hold all this information. The question is how the systems are used, how the employees are trained and last but not the least, what search criteria and patterns the company anticipates using in the future when implementing such systems. Typing errors and inconsistent conventions for naming of components complicated the data retrieving even further.

The main experience to report from this part of the work is that many modern companies do have the opportunity to use their data management systems much more efficiently. Again, it is my strong believe and experience from other companies, that this is by no means a case specific to the case company.

Lack of appropriate software tools

Different software tools have been applied when building the tool, but especially trivial software such as Microsoft Excel. Though, Microsoft Excel is not a tool minded for graphical illustration the dominance of Microsoft Office products has made most people familiar to the Microsoft environment and they will know Excel. It is important to choose a media that is readily available for the future users (in order to secure future update of information) and to choose a media and tool that is compatible with existing systems as well as the skills of the employees. In the apparent lack of appropriate software Microsoft Excel will do.

The PFMP^2 users become the experts

An interesting finding from the case work is that the tool itself is not the only benefit for the company. The process of building the poster and the knowledge and overview gained through that process is also very valuable. An important point is therefore to have company internal employees do the practical work of gathering the data and implementing the PFMP^2 modelling formalism rather than external researchers/consultants.

The process of digging through different databases in the search for information and the subsequent discussions that arise when the information has to be classified and structured on the poster is of great importance. When applying the PFMP^2 modelling formalism those responsible are forced through a process of steps in which each new phase will add to their knowledge and product family insight.

The process makes these persons key personnel in the change process and they should be chosen with this in mind before the product family assessment starts. They are the ambassadors of possible future changes and their personnel characteristics are important. They should preferably be respected and empathic extrovert people that will succeed in driving a change process, with their personality and with the knowledge they gained when making the poster. It is important to have such persons to constantly refresh the memory of a large organisation on why changes are needed and how they should be handled.

Interdepartmental understanding

Another interesting feature with the implementation process is the interdepartmental network that arises from the work. In order to make the poster those responsible has to understand many different aspects of the company, and thus has to interview or collaborate a variety of people in different departments.

As the prescribed tool in this research work highlights existing inexpediencies inside the organisation it forces the involved people from different departments to get together and solve the inherent and often invisible problems inside the company. The networking aspect of this process is invaluable as those key employees taking part of this work will help tie together different departments in the future as they get an understanding of the consequences causes in other departments due to the decisions they make in their own department, i.e. dispositional relation.

Graphical skills

Engineers are trained to make products or production lines work. Consequently, they are focused on functionality and thus they want to ensure that all details are working. The most widely used product model for an engineer is a technical drawing and/or a CAD assembly. Technical drawings and CAD assemblies are very detailed. Basically, creating an overview of a product family is another modelling discipline than that of making technical drawings and some graphical skills is needed in the process as the overview tends to drown in irrelevant information if one solely relies on technical drawings and CAD models.

Allocating resources in the organisation

Allocating the right amount of resources is – not surprisingly - very important. Depending on the state and accessibility of data and information it may take a person everything from a few days to several months to gather all the information necessary to paint the overview on a poster. Building the poster itself is a potentially time consuming work as well.

Management has to support this work. In the beginning of the process it might be beneficial to have someone from outside the company or business unit to start the work because a very important part of the process is to ask all the "stupid" questions. In a mature product range there will be many design features that are present simply because "they have to be" and not for a specific reason. Having said this, you also need in the process the support from experienced domain experts throughout the company, such as an experienced purchaser, engineering designer or production manager.

Part 8

Conclusion

The objective of part 8 is to recapitulate the results of the research work including giving answer to the research questions that were formulated at the beginning of the research and summing up the contribution from this research work. Part 8 also elaborates on the experiences that were made during the practical implementation of the research results at the case company Danfoss AC and the limitations of the developed support. Finally, part 8 points out areas for future research.

8.1. Concluding the research questions

A conclusion on this research is an evaluation of whether or not the research gives an answer to the research questions given at the beginning of the thesis. Moreover, a research question is a question that is *expected* to call for an answer, i.e. the relevance of the topic and questions raised might not be fully explored at the beginning of the study. Anyhow, the relevance of the topics and the applicability of the research results become clearer as the study progresses and it therefore seem fair – apart from the research itself - to also conclude on the applicability of the results in industrial practice. This is a natural characteristic of research in design methods and it also complies with the research approach described in Part 2, specifically the model from [Jørgensen, 1992], in which research and development goes hand in hand.

The research questions were formulated in the section, '1.5. Research questions'. In the following section I will elaborate how the research questions have been addressed in this work.

8.1.1. Research question 1

The first research question was;

Research question 1

> *What information and data elements – especially about product design and production setup - are required in the assessment of a product family's performance regarding effective and efficient production of value-adding product variety, and what elements should then consequently be taken into account when re-considering the design of the products in the product family and/or the coherent production setup?*

The descriptive study of this research work revealed elements that influence a product family's performance regarding the ability to create product variety efficiently and effectively. The list of identified information elements that would strengthen the decision foundation comprises the following;

- *Customer perceived product offering*
  An overview of the product variety offered in the market when evaluating the goodness of a product family. Basically we need to answer the question: "*Do we offer the right products?*"
- *Value of variety*
  The variety within the product family can be classified as either value-adding, non value-adding or necessary variety. In a re-design process non value-adding and necessary variety should preferably be eliminated.

- *Causal links*
  Causal links describes either *"is realised by"* or *"contribute to"* relations. The former explaining e.g. how a certain function is realised by physically, the latter explaining e.g. how a physical component contributes to compose a certain product feature.
- *Product structure*
  Assessment of a product family should hold information about the structure of the products in the product family, including information about variety aspects in the product family and the interrelating constraints, which determines what elements that can be combined to form a complete product.
- *Life phase system relations*
  Relations between product and production domains should describe the consequences in production setup of decisions made in the product domain and vice versa, i.e. elements in the product design that are a consequence of decisions made about the production setup.
- *Point of variegation*
  One of the keys to effective production of product variety is to postpone the task of differentiating a product for a specific customer until the latest possible point in the supply chain system, i.e. postponing the point of variegation. Understanding the where the products become specific is consequently relevant when assessing the product family.
- *Production/supply chain system*
  Understanding the structure of the production and the processing steps necessary to produce the products is a prerequisite to identify life phase system relations and the point of variegation. Furthermore, value of variety in the production setup should be evaluated equally to variety in the product design, i.e. identification of value-adding, non value-adding and necessary variety.
- *Strategic importance*
  It should be possible to accentuate product variants, features, functions, etc., which for some not directly measurable reason have strategically importance to business.
- *Critical design issues*
  To avoid repeating earlier design inexpediencies in the re-design of the product family, information about such critical design issues that have been encountered in the past should be collected as part of the assessment process.

A detailed description of the required elements can be found in part 4, 'Requirements'.

8.1.2. Research question 2

The second research question was;

Research question 2

> *How can these different types of information and data elements (research question1) be refined and presented in way that it links the various types of information and data in order to visualise relations between the products' design and life phase systems related to the production and supply chain – providing the necessary details and, yet, still maintain the overview in order to support and improve decision-making related re-design of the products in a product family and/or the coherent productions setup?*

The response and subsequent answer to the research question has been to develop a visual modelling formalism by which information and data can be refined and specifically presented, and when done in the prescribed way, it improves the foundation upon which decisions are made.

The PFMP[2] modelling formalism reported in this thesis includes four different modelling elements:

- *PFMP*
  The PFMP modelling element presents structural elements of the actual products in the product family, and the variety of features, functions and parts/assemblies. The PFMP modelling formalism as it is presented in this work holds elements of *product structure*, *customer perceived product offering*, *causal links* and *value of variety*.
- *Supply chain analysis*
  The supply chain analysis describes the flow of materials through the various production processing steps that are used to produce all the variants in the product family. The supply chain analysis includes elements of *production/supply chain system*, *point of variegation* and *life phase system relations*.
- *Overview of the total product offering*
  The overview of the total product offering presents statistical sales data and marks strategically important product variants and hereby helping to prioritise in a re-design process. This modelling element captures elements of *value of variety*, *strategic importance* and *customer perceived product offering*.
- *Overview of critical design issues*
  The overview of critical design issues include a visual representation of design issues – solved or unsolved – that should be considered during a re-design process to ensure product quality. This modelling element holds information about *critical design issues*.

The modelling elements are linked together using cross referencing and simple colour coding which makes it relatively easy to relate information from one view to information in the other views, i.e. it becomes possible to track to what extend specific product variants, parts, features, processing steps and technologies contribute to the business and the complexity within the product family.

The prescribed support, the PFMP^2 modelling formalism, has shown the potential to hold a vast variety of information in a - relative to the onset of the information storage - simple visual model.

Regarding the aspects of supporting and improving decision-making, the main response has been very positive and most of the reviewers acknowledge the intended benefits of the tool and in particular the main benefit related to the research question: The tool is applicable as a decision making foundation in complex product families.

One thing is mentioned several times by reviewers and practitioners in general. The information on the tool is printed on a large piece of paper as a poster. The poster format, as opposed to virtually any computer based system, gives the opportunity to overlook large data sets from an entire product family, while still maintaining an overview.

8.2. Research contribution

The research contribution to report from this work is the formulation of the *extended product family master plan* - PFMP^2 and the documentation of effects of its application. PFMP^2 contributes to a modelling formalism that can be used for assessing a product family's performance regarding effective and efficient production of value-adding product variety.

The modelling formalism was developed as a response to the two research questions and as a result of the initial descriptive study, in which the need for a new information processing method was identified.

The key contribution of the modelling formalism is the simultaneously modelling of aspects of the products' structure and the coherent flow of materials through the processing steps in the production setup, the linking of these and hereby make life phase system relations visible – i.e. relations between variety the design of the products in a product family and the life phase systems related to the production of the product variants in the product family. This reveals and visualises the consequence in the production setup and the complexity of these systems due to variety in the products' design. Existing assessment and modelling tools - like e.g. the PFMP which the modelling formalism builds upon or value stream mapping tools – focus on either the products' structure or the production setup, but not the linking of these.

The PFMP[2] holds information on product variety within in the product family, the reason (or lack of reason) for this variety (through the modelling element that presents an overview of the total product offering) and finally combines this knowledge with an understanding of the consequences in the production setup.

Building a model that unites information about customer preferences, product constituents and production flow creates a strong understanding in the minds of those who make the model, e.g. a design team. Moreover, the visual nature of the model makes it easy to pass on the message and a foundation for conclusions and decision making is readily available for management even though they seldom take part of the detailed work in such an analysis.

The application of the PFMP[2] indicates usefulness of this tool as a support for decision making regarding re-design of a product family. The reviewers that have taken part in this study acknowledge the potential benefits of the tool and generally stress that they would expect this tool to be of great help in their specific working environment. The general validity of must though be supported by more empirical studies in further research.

This thesis present an approach to modelling of product families that consist not only of the formalism, but also of a set of activities that support the process of implementation and hereby contributes to the effect of modelling tool. Hereby the modelling formalism provides a natural starting point in any change process related to complex and mature product families, that has lacked prior, and it can provide design teams and management with a diagnosis that can highlight potential areas of improvement and spark ideas for future change.

8.3. Reflection

The research has provided a tool for analysis decision-making if the company decide to "trim" the product family, e.g. by discontinuing those variants that add to complexity without adding significantly to the contribution or completely re-designing the product family. The result would be a cut down in complexity. But if there is no change in the habits and working patterns of the employees one cannot expect the growth of complexity to stop. After a while, the company is likely to end up in a similar situation – struggling with product complexity. The company will have to change it workings procedures and habits to control the growth of complexity.

As discussed earlier in this thesis, a mass customization strategy and the use of product platforms is one option for a company trying to deal with complexity in a long term perspective.

An analysis like the one described in this thesis only highlights potential problems and inspires to possible solutions. It does not constitute a change in working patterns and the products do not change automatically.

8.3.1. Future research

The PFMP[2] modelling formalism still has some aspects that are relevant to investigate in future research.

The validation in this study has been obtained only by speculation. The reviewers of the work have been presented before the tool and have been asked to judge it in order to built confidence in the usefulness of the tool. But clearly it is hard to find a research setup in which a full scale test of the tool could give clear and unbiased conclusions. Other initiatives in the companies, changing state of markets with slumps and booms, changing employees, and so on, will blur the picture of the exact effects of the tool. Also application of the formalism in other cases would improve the validity of its effect.

If the study was to be replicated in another setting – say another business setting or company – the first thing to do, would probably be to set up a situation in which one could study the effects with and without the tool. Multiple cases would add to the validation of the tool. But there is still an inherent problem in that it is hard to determine the effects of a better decision foundation.

Market aspects and the incorporation of information on market segments, customer habits, marketing research with statistics on key aspects, would be beneficial in the decision making process. That is of particular interest should the company decide to induce a change process after the analysis is done. It is very important to know the present virtues of a product family before changing anything. You might end up destroying a good business if too many changes are implemented.

As of today the PFMP[2] modelling formalism is mainly used to get an overview in the form of a static picture to put on the wall. There are no intelligent search options, and the information is not directly and automatically updated from the various databases. Building the tool is also done on the basis on spreadsheets and flowchart programmes like MS Excel and MS Visio. The functions of the tool are quite simple: The ability to set up pictures, tables, product structures, flowcharts and relation matrices is the key functionality used in the PFMP[2]. At present there is a newly started company marketing a tool that can build an object oriented product model. It would be interesting to explore the future possibilities of that software tool.

In the global market companies are struggling to meet customers' expectation of products that are – at a relatively low price - custom fitted to suit their exact needs and at the same time maintain a profitable business. In the pursuit of growth companies tend to focus on customer demand and market driven product development. While operating in the mass production paradigm and focusing on the cost of the single product this will in time lead to a patchwork of product variants, features, parts, and process technologies.

As a consequence there has been an increase in the number of companies that are beginning to change their focus from single products to entire product families and try to incorporate the development of product variety into a future product family. The key is to create fit between the product design and production setup.

This research contributes with a visual modelling formalism, PFMP2 – the extended Product Family Master Plan. The model can used to build an overview of dispositional relations between the design of a product family, the production setup and commercial aspects.

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